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Assessment of Advanced Building Air Filtration Systems

FINAL REPORT

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FINAL REPORT ON

Assessment of Advanced Building Air Filtration Systems

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List of Acronyms

ASHREA	American Society of Heating, Refrigerating and Air-Conditioning Engineers
CB	chemical/biological
CBIAC	Chemical and Biological Information Analysis Center
CMD	count mean diameter
DTIC	Defense Technical Information Center
EEF	electrically enhanced filter
EPA	Environmental Protection Agency
HEPA	high-efficiency particulate air
HVAC	heating, ventilating, and air conditioning
KCl	potassium chloride
MERV	Minimum Efficiency Reporting Value
NTIS	National Technical Information Service
ORD	Office of Research and Development
QF	quality factors
SMPS	Scanning Mobility Particle Sizer
TOPO	Task Order Project Officer

Executive Summary

The original purpose of the work described in this report was to develop an advanced air filtration system that could be adapted to a building's heating, venting, and air-conditioning (HVAC) system to help protect the building from an attack with a biological agent. It was desired that the advanced filtration system provide lower pressure drop than conventional high-efficiency particulate filters with higher or equivalent efficiency and comparable or lower cost. Through literature searches, market surveys, technology assessments, and discussions with air filtration system manufacturers, it was determined that new technology was not adequately advanced to merit development of an advanced HVAC particulate removal system for this project. Improvements in technologies were identified, but nothing that could improve performance much beyond what existed in current or soon to be commercially available products. Therefore, in lieu of describing the development of an advanced filtration system, this report provides an assessment and discussion of advanced particle removal technologies for HVAC systems.

As the first step of this study, the performance requirements of an advanced filtration system were established to provide a basis for evaluation of candidate technologies. The requirements were established considering two criteria: (a) the technology has better performance than the high efficiency filters (MERV 14, 15, and 16 filters) available in the market and (b) the technology does not exceed the pressure drop limit that common HVAC systems can accommodate. Based on these criteria, the performance requirements established were a 99.9% removal efficiency for aerosols with a 1-µm diameter (optical diameter) and with a pressure drop of less than 0.5 in. H_2O.

A comprehensive literature search was conducted to identify advanced filtration technologies and manufacturers that could potentially be used in the advanced filtration system. The databases searched, including CBIAC, DTIC, CA Search, NTIS, Energy SciTec, Ei Compendex®, SciSearch®, and Biosis Previews®, covered a wide variety of technical journals, conference proceedings, patents, government reports, and books. A market survey was conducted simultaneously with the literature search through the Internet, phone conversations, and meetings with leading filter/filter-media manufacturers at professional conferences.

Three filtration technologies were identified as preliminary candidates for an "advanced" system: electret filters, electrically enhanced filters (EEFs), and nanofiber media filters. The operation principle, potential drawbacks, technology maturity, ability to meet the performance requirements, and cost of each candidate technology were assessed. Upon further analysis, EEFs were rejected as an advanced filtration technology because of their relatively high cost compared to conventional filters, as well as their potential diminished collection efficiency with dust loading.

Sample electret and nanofiber media were requested from manufacturers. Screening tests were conducted to measure the initial aerosol collection efficiency and airflow resistance. As shown in Equation ES-1, the performance of the candidate media was compared to the performance requirements and ranked using a systematic parameter called quality factor (QF):

$$QF = \frac{(-\ln p)}{\Delta P \times \delta} \qquad \text{(ES-1)}$$

where: p is the penetration fraction of 1-µm particles,

ΔP is the pressure drop (mmH_2O), and

δ is the filter media thickness (mm).

Three candidate nanofiber media with different expected collection efficiencies were tested but demonstrated QFs significantly lower than the hypothetical advanced filter QF. Therefore, the nanofiber technology was excluded from further evaluation. Among the eight electret media tested, three demonstrated QFs higher than the performance requirements. In other words, those three media offered lower penetration, lower resistance, and/or were thinner than a filter just meeting the specification.

The literature reported the potential degradation of electret filters with aerosol loading and the importance of identifying the minimum collection efficiency of an electret filter within its service life (Lehtimäki and Heinonen, 1994; Lehtimäki et al., 1996; Lifshutz, 1997; Pierce and Lifshutz, 1997; Barrett, 1998; Hanley et al., 1999; Raynor and Chae, 2002; Raynor and Chae, 2003). Thus, a laboratory conditioning method was developed by Hanley and Owen (2003) to try to identify the minimum collection efficiency of an electret filter. The three electret sample media that demonstrated promising QFs were conditioned in the laboratory using a nano-sized KCl aerosol, according to the method developed by Hanley and Owen (2003). The candidate electret samples were also conditioned with ambient aerosol to characterize the degradation in an actual ambient environment. Conditioning tests were performed in incremental steps, with efficiency measured after each increment, to identify the minimum collection efficiency.

Among the three sample media tested, only Sample G demonstrated excellent efficiency stability. Both initial and minimum collection efficiencies of Sample G (based on laboratory conditioning) met the efficiency goal of 99.9% for 1-µm diameter particles. The initial airflow resistance, however, was approximately 6% higher than the "advanced" filter performance requirement. The slightly higher airflow resistance can be reduced by enlarging the filter media design area to over 100 ft^2 (i.e., the design area that the media evaluation tests are based on), which is attainable since a typical pleated high-efficiency HVAC filter usually has media area ranging from 100 to 180 ft^2.

In conclusion, tests conducted in this study with swatches of candidate filter media demonstrated the potential to develop an advanced electret filter that can meet the performance goals. It was determined, however, that the incremental gain in collection efficiency and reduction in airflow resistance were not sufficient to merit continuing with the development of the advanced filter under this project. Furthermore, the manufacturer of the leading media (Sample G) indicated that they had already planned further improvements to that media and that a filter made of the improved media was being tested and was expected to be on the market soon.

1.0 Introduction

Buildings can be vulnerable to terrorist attacks using various types of threat agents. The most serious effects of such an attack are on the health of the occupants of the buildings. Building occupants may suffer health effects ranging from irritation, to severe sickness, to death. The attack may also have long-term economic and other impacts due to building contamination. Although guidelines exist, there is still some uncertainty as to the optimum course of action to take in mitigating the impact of a terrorist attack on a building. Tools and technologies to implement optimum courses of action are often not available, are too expensive to use, or are insufficient.

2.0 Objective

The original purpose of the project described in this report was to develop an advanced air filtration technology that could be adapted to a building's HVAC system to protect a building from a biological attack. The advanced air filter would provide a lower pressure drop than conventional high-efficiency particulate filters (MERV 14, 15, and 16 filters) but with higher or equivalent efficiency and comparable or lower cost. But as explained in the following sections, the focus of the project switched from the *development* of an advanced technology to an assessment of currently advanced technology.

3.0 Scope

The first step of the project was to conduct a literature review and market survey to: (a) identify candidate advanced air filtration technologies that could potentially be used in protecting the indoor environment from biological agents and (b) establish performance requirements for the advanced filtration system to be developed. The approaches and results of the literature review are presented in Section 4.0 of this report.

Sample candidate filtration media (based on two filter technologies) identified in the literature review were requested from the corresponding manufacturers. The sample media were evaluated experimentally to explore the feasibility of developing an advanced filtration system that can meet the performance goals. The test methods, data collected, and the results of the evaluation tests are presented in Section 5.0.

Based on all of the efforts of this project (literature searches, market surveys, technology evaluations, and discussions with air filtration system manufacturers), it was determined that new technology was not adequately advanced to merit development of an advanced particulate removal system under this project. Improvements in technologies were identified, but nothing that could improve performance much beyond what was already available or soon to be commercially available. Nonetheless, an assessment and discussion of advanced particle removal technologies for building HVAC systems is provided.

4.0 Literature Review and Performance Assessment

4.1 Literature Search

A literature search was conducted to identify advanced filtration technologies that could be developed for an HVAC system. Eleven databases — CBIAC, DTIC, CA Search, NTIS, Energy SciTec, Ei Compendex®, SciSearch®, Biosis Previews®, Enviroline®, World Textiles, and Textile Technology Digest — were searched through the Chemical and Biological Information Analysis Center (CBIAC) and the Dialog online information systems. These databases were selected to ensure that the literature search covered a wide variety of technical journals, conference proceedings, patents, government reports, and books. Brief descriptions of the eleven databases are presented in Appendix A.

Based on information obtained in related research regarding air filtration, the literature search first focused on the following technologies: (1) electret filtration media, (2) nanofiber filtration media, (3) filters with biocides, and (4) layered composite filters. A more general search was also conducted to identify other potentially advanced technologies in the air filtration area. The search strategies and the corresponding hits generated are summarized in Table 1. Note that the initial search in the area of electret filtration media generated a large number (12,000) of hits. Subsequently, the search was narrowed using the keywords "review(s) or survey(s)."

A total of 2,060 hits were generated using the search strategies presented in Table 1. The titles and/or abstracts of the 2,060 hits were screened, and 50 relevant articles were identified and ordered. Relevant articles collected for other previous related research were also reviewed. Note that no relevant articles were identified for the layer composite technology, so this was removed from the candidate list of technologies.

In addition, a market survey was conducted through the Internet, phone conversations, and meetings with potential leading manufacturers at professional conferences. A brief Internet search was conducted to identify manufacturers in the areas of electret media, nanofiber media, and any other novel media that had high efficiency and relatively low pressure drop. Battelle staff also met with sales and technical representatives from the major filter and filtration media manufacturers during the Filtration 2004 International Conference and Exposition on 7–9 December 2004, in Philadelphia. Follow-up phone discussions were held with the manufacturers who carried the products of interest to request further technical and cost data for a preliminary screening and evaluation.

Table 1. Literature Search Strategies and Summary Results

Target Area	Search Strategy	# of Hits	# of Articles Ordered
Electret Media	{filter? or filtration or media} and {electret? or electrostatic?} and {review? or survey?}	374	25
Nanofiber Media	{filter? or filtration or media} and {nanofiber? or nanofibre?}	256	7
Biocidal Media	{filter? or filtration } and {biocidal}	100	7
Layer Composite Media	{filter? or filtration } and {layer?(5N) composite?}	251	0
Advanced and Novel filters	{air} and {filter?} and {advanced? Or novel or (state (2w) art)}	474	5
Air Filter Review	{air} and {filter?} and {review? Or survey?}	605	6
Total		**2060**	**50**

4.2 Establishment of Performance Requirements

Currently, there are no performance criteria established for HVAC air filtration systems designed to protect building occupants against biological agents. To help down-select technologies for consideration in an advanced filtration system, performance requirements were established based on: (a) the collection efficiency of filters available in the market, (b) the range of aerosol sizes expected to be representative of bio-terrorist attacks, and (c) the maximum pressure drop that common HVAC systems can accommodate.

A brief market survey was conducted to identify the best filters available in the market for commercial HVAC application. Although high-efficiency particulate air (HEPA) filters provide high filtration efficiency, they are not necessarily appropriate for HVAC applications. As a general rule, existing HVAC systems cannot be upgraded to HEPA filters without a complete retrofit of the air handling system due to the high pressure drop and potential leakage associated with them. Instead, filter manufacturers (AAF International, 2005; AIRGUARD, 2004) recommend high-efficiency filters (MERV 15 and 16) as a cost-effective alternative to HEPA filters to protect commercial buildings against bio-attacks.

Table 2 lists a sample of the high-efficiency filters available in the market as well as a summary of their performance and cost. As shown in Table 2, the leading high-efficiency filters in the market demonstrate comparable performance. The filters with uncharged media can provide efficiency ranging from 96 to 99% for 1-µm diameter particle and pressure drop ranging from 0.4 to 0.6 in. H_2O, with a cost ranging from \$170 to \$230. Special designs such as V-bank, mini-pleat, or V-shape pleat are applied in these filters to reduce pressure drop.

The high-efficiency electret filters can provide a slightly lower pressure drop (0.27 to 0.35 in. H_2O), but with an equivalent initial efficiency (95 to 98% for 1 µm) and lower cost compared to the uncharged filters. The potential degradation of the commercial electret filters, however, remains a concern.

The performance of the high-end filters in the market was used to establish the performance requirements of an advanced filtration system. The priority of performance criteria in developing the advanced filter, in decreasing order of importance, is pressure drop, collection efficiency, cost, and size.

Table 2. Leading High-Efficiency Filters Available in the Market (Filter Size: 24" x 24" x 12")

Media Type		Manufacturer	Model	Filter Type	η[a] for 1 µm @500 fpm	Initial ΔP (in. H_2O) @500 fpm	Cost($) per filter (2,000 cfm)
HEPA	[b]	[b]	[b]		> 99.99	1 to 2	180 to 500
Uncharged	Microglass paper fibers	AAF	VariCel® V	Mini-pleat, V-Bank	97%	0.59	170
	Synthetic media	AIRGUARD	VARI+PLUS®VP	Mini-Pleat, V-Bank	≥ 96%	0.4	231
	Glass fiber papers	Freudenberg	Viledon® MX98	V-shape pleats, box	≥ 99%	0.46	-[c]
Charged	Synthetic media	Freudenberg	Viledon® MV95	Pleat, V-Bank	≥ 98% (initial)	0.35	152
	Synthetic media	TOYOBO	SL-56-95T	Pleat, Box	95%	0.27	-[c]

[a] η is defined as collection efficiency.

[b] Representative of a typical HEPA filter is AstroCel HCX (HEPA) filter from AAF® International.

[c] The cost was not provided by the manufacturer.

The performance goal for collection efficiency was specified for 1-µm particles because most bio-aerosol challenges are expected to have diameters equal to or larger than 1 µm. Furthermore, only aerosols with diameters ranging from 1 to 5 µm can be transported long distances by wind without decay and can be inhaled deeply into the lungs (Edward, 1997). The market survey revealed that the high-efficiency filters currently commercially available could achieve a collection efficiency near 99% for 1-µm particles. For the hypothetical advanced filter being considered in this study, it was determined that the collection efficiency would have to be an order of magnitude better, i.e., it would have to have an efficiency higher than 99.9% for 1-µm particles.

The performance goal regarding pressure drop was set to be less than 0.5 in. H_2O at a face velocity of 500 fpm to ensure the advanced filter could be used in an existing HVAC system without extensive modification (i.e., retrofitting with a larger blower unit). Pressure drop across the mechanical filters in a typical HVAC system in a standard office building is generally less than or equal to 0.5 in. H_2O. By setting the performance goal to be less than 0.5 in. H_2O, the developed filter could be installed into a standard office building HVAC system without modifications. In comparison, if a HEPA filter were installed into an existing HVAC system, major modifications would need to be made since the pressure drop of a HEPA filter typically ranges from 1 to 2 in. H_2O.

To ensure the comparison of technologies is made on an equivalent basis, the required efficiency and airflow resistance listed in Table 3 are based on an air handler capacity of 2,000 cfm and filter dimensions not larger than 24" × 24" × 12".

Table 3. Performance Requirements of the Advanced Filtration System

Filter Parameter	Goal
Efficiency	≥ 99.9% for 1-µm aerosol (At 2,000 cfm or 500 fpm)
Airflow Resistance	≤ 0.5 in. H_2O (At 2,000 cfm or 500 fpm)
Filter Dimensions	≤ 24" × 24" × 12"

4.3 Candidate Technologies Assessment

Based on the aforementioned literature review, market survey, and discussions with sales/technical representatives from major manufacturers of air filters, the following technologies were identified as candidates for the advanced filtration system: (1) electret filters, (2) electrically enhanced filters (EEF), and (3) nanofiber media filters. No promising filters were identified using biocidal additives or layered composite technology. The candidate technologies are described and assessed in the following sections.

4.3.1 Electret Media

4.3.1.1 Technology Description. Many air filters in the market are currently manufactured using electrically charged media to attract particles. This improves a filter's efficiency without increasing its pressure drop. Filters that use this technology are commonly referred to as "electrostatic," "electrically charged," or "electret" media. The advantage of electret media is their relatively high collection efficiency at relatively low pressure drops, when compared to filters relying solely on mechanical means for particle capture.

Electret media are made of dielectric materials that have a significant microscopic bipolar charge on the fibers and a very low net macroscopic charge. Unlike the electrically enhanced filters described in Section 4.3.2, electret media are permanently charged during media manufacturing. Therefore, electret media do not require an electrode system to charge filter media or an ionizer to charge incoming particles during operation. Electret filters collect particles through a combination of conventional mechanical mechanisms (i.e., impaction, interception, and diffusion) and electrostatic mechanisms (i.e., Coulombic attraction and dielectrophoretic capture). Charged particles are attracted to oppositely charged fibers by the Coulombic force. For singly charged particles, the attraction increases as particle size decreases. Neutral particles that are unaffected by Coulombic force are collected by dielectrophoretic force—the polarization force induced by local electrical fields within the filter media. Charged particles are also collected by dielectrophoretic capture. The efficiency of the dielectrophoretic capture increases with particle size.

The efficiency of electret media depends on parameters such as charges on particles, charge density of fibers, and chemical compositions of particles and fibers; efficiency also depends on factors that affect the efficiency of conventional uncharged filters, such as fiber diameter and packing density of the fibrous materials.

There are many types of electret media, due to the variety of fiber-forming technologies (i.e., meltblown, split fiber, bi-component spunbond, needlefelt) and the variety of electrostatic treating technologies (i.e., corona charged, triboelectric charged, induction charged). The composition of electret media varies from polycarbonate, polypropylene, and polyolefin to a binary mixture of polypropylene and chlorinated acrylic fiber. Because the media are manufactured using different technologies and are composed of different polymers, there is a significant range in filtration performance and degradation behavior (Barrett and Rousseau, 1998; Romay et al., 1998).

4.3.1.2 Potential Drawbacks. A concern with using electret filters is the effect of aerosol loading on collection efficiency. The collection efficiency of an electret filter for solid particles has been found to decrease with operation time in its early stage of collection until it loses electrical forces. At that point, the collection efficiency stabilizes but then increases with time because the filter media become loaded with the solid particles (Myers and Arnold, 2003).

Electret filters also degrade when loaded with oil aerosols (Lehtimäki and Heinonen, 1994; Lifshutz, 1997; Pierce and Lifshutz, 1997; Barrett and Rousseau, 1998). Oil-resistant electret filters, which have much lower degradation by oil aerosols, were developed and used in particle respirators (Barrett and Rousseau, 1998; Romay and Liu, 1998; Janssen et al., 2003a and 2003b). Because oil aerosols are not the major components of ambient/indoor aerosols, the assessment in electret degradation of this study focused on the degradation by solid aerosols.

Arizona road dust is the ASHRAE test dust that is currently used in the conditioning step of the ASHRAE Standard 52.2. Several studies (Lehtimäki, 1996; Hanley et al., 1999; Raynor and Chae, 2002; Raynor and Chae, 2003) revealed, however, that the degradation of the electret filter, when loaded with the ASHRAE dust, is less significant than when the filter was exposed to real ambient conditions. These studies revealed that the ASHRAE 52.2 dust-loading procedure does not adequately reproduce the reduction in filtration efficiency that an electret filter encounters in actual HVAC systems. The ASHRAE Standard 52.2, which was developed to determine the minimum efficiencies of a filter over its lifetime, may actually provide an artificially higher MERV rating for an electret filter.

Realizing the potential deficiency of the ASHRAE Standard 52.2 that tends to show an artificially higher MERV rating for electret filters, the ASHRAE committee supported a research project conducted by Research Triangle Institute (RTI) to develop a dust for a new loading test method that will more accurately determine the minimum efficiency points of an electret filter in a real-world application (Hanley and Owen, 2003). Under this project, a new loading test method was developed to replace the first dust loading step (or the conditioning step) of ASHRAE 52.2, using a nano-sized solid-phase KCl aerosol (with number mean diameter of 0.035 μm) as the conditioning aerosol. The new method provided a means of accelerating the decrease in efficiency that electret filters undergo in real-life applications. A draft addendum (Addendum C) to ASHRAE Standard 52.2 was prepared during the project. The addendum includes a detailed protocol of conditioning the electret filters using nano-sized KCl aerosols to mask (or screen) the charges on the electret filter. ASHRAE Standard 52.2 Addendum C is currently available for public review.

Despite the potential efficiency degradation of electret media with use, they have gained significant market share and acceptance in HVAC filtration applications over the past few years (Arnold and Myers, 2002; Homonoff, 2004). This is because electret filters are usually less expensive than mechanical filters (glass fiber filters) with the same MERV rating. In addition, in spite of the collection efficiency degradation, the efficiency of an electret filter will always exceed that of an uncharged filter with the identical mechanic structure.

When selecting an electret filter for an HVAC filtration application, it is important to evaluate the electret filter performance data at specific application conditions. If in-use performance data are not available, a laboratory loading test (which can represent the minimum efficiency points of an electret filter in a real-world application) should be conducted to ensure the selected electret filter can meet the design goals of a particular HVAC application.

4.3.1.3 Technology Maturity for Use in the Advanced Filter. In the HVAC filtration market, electret filters are finding increased popularity (Myers and Arnold, 2003; Homonoff, 2004). Nearly all high-efficiency (MERV 11 or higher) residential filters are composed of electret material as well.

The electret filters available for residential HVAC filtration generally have MERV ratings ranging from 8 to 12. The typical pressure drop for residential pleated electret filters ranges from 0.13 to 0.35 in. H_2O at 300 fpm (3M Brochure, Improve Indoor Air). The electret filters used for commercial HVAC filtration generally have MERV ratings ranging from 8 to 16. The two major manufacturers of electret filters are Freudenberg Nonwovens and the 3M Company.

Freudenberg, a leading manufacturer of commercial HVAC electret filters, developed and patented a process in which polymer fibers (e.g., polycarbonate fibers) are spun in an electrostatic field. This process is known as the electrostatic spinning process. Since the fibers are manufactured in an electrostatic field, they carry an electrostatic charge, which significantly improves the collection efficiency.

Freudenberg's pleated electret filter, Viledon® MV95 (MERV 15), as shown in Table 2, has over 98% efficiency for a 1-μm aerosol and a pressure drop of only 0.35 in. H_2O at 500 fpm. This performance of Viledon® MV95 is close to the design goals presented in Table 3. According to David Matier, Manager of North American Operations at the Freudenberg Group, the Viledon® MV95 is currently used in the HVAC systems of the federal buildings of Los Angeles and Honolulu.

The high performance of the Viledon® electret filter makes the Viledon® electret media one of the top candidates to be considered for use in the advanced filtration system. Battelle contacted and discussed with Dr. Andre Manz, a senior applications engineer at Freudenburg, the development of the advanced filtration system. According to Dr. Manz, the design goals presented in Table 3 are challenging. However, they may be achievable by improving the design of the Viledon® MV95 filter by adding more filter media.

Freudenberg sent a sample of the electret material (4 ft^2) used in the Viledon® MV95 filter to Battelle for evaluation. Samples of an MV95 filter and an MF95 filter were also received from Freudenberg.

The 3M Company specializes in producing high-end electret filters for residential HVAC application. 3M's residential electret filters, Filtrete™ Ultra Allergen, FiltreteTM Micro Allergen, and Filtrete™ Dust & Pollen filters are rated as MERV 12, 11, and 8, respectively.

3M fabricates three types of electret: corona-charged split-fiber media, corona-charged meltblown media, and advanced electret media. The corona-charged split-fiber media, with a commercial name of Filtrete™ Type G, are made from fibrillation of a polypropylene thin film charged by corona ions. The corona-charged meltblown media, with commercial names of Filtrete™ Types B, E, and S, are charged by corona ions during the meltblowing process. The patented advanced electret media are a new class of filter media developed by 3M and used in 3M's N95, P95, and P100 particulate respirators.

Battelle contacted Dr. Michael Strommen, the product development manager from 3M Filtration, to discuss the development of the advanced filtration system. According to Dr. Strommen, in addition to the well-known FiltreteTM electret filters for residential HVAC applications, 3M also fabricates high-efficiency electret filters for commercial HVAC applications. The technical data sheet of a 3M commercial high-performance HVAC filter (MERV 14) was sent to Battelle. Similar to Dr. Manz, Dr. Strommen also believed the design goals were challenging but may be achieved using a V-bank design to accommodate more filter media.

Samples of two grades of 3M meltblown electret media were sent to Battelle in April 2005. According to Dr. Strommen, the two grades are at the high end (high-efficiency, high-pressure drop) and toward the middle (mid-efficiency, mid-pressure drop) in terms of performance, for the media that 3M can manufacture. As such, these samples should bracket the performance requirements. 3M has the ability to customize the media to achieve the required performance for a given application.

In addition to Freudenberg and 3M, there are many other electret filter/media manufacturers. The major manufacturers identified in this project, as well as their contact information, are listed in Table 4. Table 5 summarizes the performance and cost data collected in the market survey for candidate electret media. The performance and cost data presented in Table 5 were either obtained from the manufacturers' product brochures or provided by the manufacturers directly.

Table 4. List of Electret Filter and Media Manufacturers

Manufacturer	Trademark Name of the Media/Filter	Media Type	Contact
3M Filtration Products www.3m.com	Filtrete™ Types G, B, E, S, and 3M™ AEM	Split-fiber, meltblown, etc.	Filtration Products 3M Center, Building 60-01-S-16 St. Paul, MN 55144 800-648-3550
Ahlstrom Air Media, LLC www.ahlstrom.com	ELECTROSTAT® HP Series	Triboelectrically charged	Jeffrey Gentry 9319 Cincinnati Columbus Rd., Ste.21 West Chester, OH 45069 513-755-9222, ext.14
Aramid, Ltd. www.aramid.com	Micron®	NA	Jay Nicholson 24 New Orleans Rd. Hilton, SC 29928 843-686-2132
DelStar Technologies, Inc. www.delstarinc.com	DelPore™	Meltblown media	Andrew Platt 601 Industrial Dr. Middletown, DE 19709 302-378-8888, ext. 4081
Filtrair, Inc. www.filtrair.com	Filtrair®	Meltblown media	Jay Forcucci 600 Railroad Ave. York, SC 29745 803-684-3533
Hollingsworth & Vose Co. www.hovo.com	TECHNOSTAT	Triboelectrically charged	Per Lindblom, Director of Sales 112 Washington St. East Walpole, MA 02032 501-850-2261
Johns Manville www.jm.com	Delta-Aire™ HS Series	Meltblown media	Charles R. Granger 171 Sandreed Dr. Mooresville, NC 28117 704-799-1263

Table 4. List of Electret Filter and Media Manufacturers (Continued)

Manufacturer	Trademark Name of the Media/Filter	Media Type	Contact
Kimberly-Clark Corp. www.kcfiltration.com	Intrepid®	Continuous Filament Melt-spun (CFM) media	Kimberly-Clark Filtration Products 1400 Holcomb, Bridge Rd. Roswell, GA 30076 770-587-8000
Lydall Filtration/Separation www.lydallifiltration.com	LydAir MB	Meltblown Composites	Scott C. Keeler North American Sales Manager Chestnut Hill Rd, P.O. Box 1960 Rochester, NH 03867 603-332-4600, Ext. 155
	LydAir SC	Synthetic Composites	
Toyobo Co., Ltd. www.toyobo.co.jp	Elitolon® Types A, AA, U, NA, and FA	Combination of spunbonded and meltblown fibers	Mitsuhiko Akiyama AC Department 2-8, Dojima Hama 2 Chome, Kita-ku, Osaka 530-8230, Japan +81-6-6348-3372
Freudenberg www.viledon-filter.com	Viledon® MV series MF series	Electrostatic spinning	David J. Matier Manager of North American Operations Freudenberg Nonwovens Filtration Division 1304 Ramona St. Ramona, CA 92065 760-788-3833
Camfil Farr www.camfilfarr.com	S-Flo	Meltblown Synthetic	Sam Glaviano Ketchum and Walton Co, Camfil Farr Representative 1350 W. 5th Ave. Columbus, OH 43212 Phone: 614-486-5961
3M Filtration Products www.3m.com	FiltreteTM HEPA diffuser Ultra allergen filter	Split-fiber	Filtration Products 3M Center, Building 60-01-S-16 St. Paul, MN 55144 800-648-3550

NA is defined as not available.

Due to the limited performance data available, the efficiency and airflow resistance shown in Table 5 are not based on the same velocity. Instead, the velocities vary from 10 to 56 fpm, which correspond to 2,000 cfm of air flowing through media areas ranging from 36 to 200 ft^2. This velocity range, however, covers the operational condition of a typical high-efficiency, pleated HVAC filter that usually has media areas ranging from 100 to 180 ft^2.

As shown in Table 5, within the velocity range considered, all the media can provide collection efficiency higher than 84% (for aerosol size <1 µm) and airflow resistance less than 0.5 in. of water. Although 84% efficiency for 0.3 µm aerosol is lower than the performance goal, the efficiency for 1 µm could be significantly higher.

Table 5. Performance Data of Candidate Electret Media from Major Manufacturers

Manufacturer	Model	Weight (g/m^2)	η	ΔP (in. H_2O)	Pleat or Pocket	Cost ($/ft²)
3M	FiltreteTM Type G, G-200	-[a]	>99% @40 ft/min (for 1μm)	0.12 @40 ft/min	Both	-
AHLSTROM CORP.	ELECTROSTAT® HP650/410	160	95% @32 ft/min (for 0.1μm)	0.5 @200 ft/min	-	-
	ELECTROSTAT® HP650/410	670	99.996% @32 ft/min (for 0.1μm)	0.5 @40 ft/min		
DELSTAR TECHNOLOGIES INC.	DelPore™ DPB002-50PNAT	50	97% @28 ft/min (for 0.3μm)	1 @28 ft/min	-	-
	DelPore™ DPB002-90PNAT	90	99.6% @28 ft/min (for 0.3μm)	0.47 @28 ft/min		
Filtrair, Inc.	Filtrair® 95%	110	MERV14 @32 ft/min	0.08 @10 ft/min	Both	-
Hollingsworth &Vose Company	TECHNOSTAT TS100/15	115	>94% @32 ft/min (for 0.65μm)	0.03 @40 ft/min	Pleat	-
	TECHNOSTAT TS500/15	515	>99.8% @32 ft/min (for 0.65μm)	0.31 @40 ft/min		-
Johns Manville	Delta-Aire™ HS-95	128	90 to 95%@7 ft/min (for 0.3μm)	0.5 @51 ft/min	Both	0.07
Kimberly-Clark	INTREPID 95SP	-	90% @28 ft/min (for 0.1μm)	0.5 @48 ft/min	Pocket	-
Lydall Filtration/ Separation	LydAir MB CL 1909	102	95% @10 ft/min (for 0.3μm)	0.1 @10 ft/min	Pocket	0.05
	LydAir SC SC 8100	116	85% @10 ft/min (for 0.3μm)	0.5 @56 ft/min	Pleat	0.10
TOYOBO	Elitolon® U type, EF-U-98P	105	84% @20 ft/min (for 0.3μm)	0.28 @20 ft/min	Pleat	-

[a] Data are not available from the manufacturer.

In addition to Freudenberg and 3M, Battelle also spoke with other electret filter/media manufacturers, including TOYOBO, Kimberly-Clark, Hollingsworth & Vose, and Lydall. Sample media were requested from the candidate manufacturers listed in Table 5 and were evaluated in the candidate media screening tests described in Section 5.0.

4.3.2 Electrically Enhanced Filters

4.3.2.1 Technology Description. An electrically enhanced filter (EEF) is a technology that can provide bactericidal activity, relatively high efficiency, and low pressure drop. The technology has been studied extensively (Bergman et al., 1983; Jaisinghani et al., 1998). An EEF usually contains an ionizer for charging the incoming particles, a filter element for collecting particles, and an electrostatic field across the filter element for enhancing the collection efficiency.

The operation principle is to ionize the incoming air stream and particles such that a surface charge is achieved on the incoming particles upstream of the filter. Charging these particles will increase both their electrical mobility as well as the attractive force to oppositely charged surfaces. Fibrous filter media are located between a negatively charged electrode upstream and a positively charged electrode downstream. When power is applied to the electrodes, an electrical field is generated, and the fibrous filter media are polarized (i.e., the fibers of the media form areas of negative and positive charge). In this manner, it is similar to that of electret media. In the case of the electrically enhanced filter, the fibers are not permanently charged like those of electrets, but rather are charged only in the presence of the electrical field.

Particle collection thus occurs predominantly due to the electrostatic forces. Because particle collection is predominantly associated with electrostatic force, larger fiber diameters of the fibrous filter can be used, allowing lower airflow resistance. Rather than increase the collection efficiency of a fibrous filter by reducing the fiber diameter and thus increasing the pressure drop, the collection efficiency is enhanced by charging the particles and polarizing the fibers.

4.3.2.2 Potential Drawbacks. The major drawback of an EEF system is the potential increase in current through the filter element when the challenging aerosol contains conductive particles. For example, 20% of the ASHRAE test dust (the Arizona Road Dust) is conductive. The increase in electric current can automatically reduce voltage and subsequently lead to a reduction in efficiency. The current increase may also lead to shorting out of the whole filtration system.

High cost is another disadvantage of the EEF system. The initial cost of an EEF system is approximately more than 3.5 times the cost of an uncharged high-efficiency filter and more than 5 times the cost of a high-efficiency electret filter. In addition, there are extra costs for installation, maintenance, and operation compared to a conventional filter system.

Table 6. Performance Data of Electrically Enhanced Filter Systems

Manufacturer	η %	ΔP	Filter Dimensions	Filter Cost
StrionAir	95% (initial)[a] (for 1µm) (@ 1640 cfm or 500 fpm)	0.43 in. H_2O (@ 1640 cfm or 500 fpm)	20" × 24" × 12"	EEF system: $800/2000 cfm; plus Disposal filter: 95/2000 cfm
Technovation Systems, Inc	≥ 99.97% (initial) for 0.3µm (@ 2400 cfm or 600 fpm)	0.5 in. H2O (@ 2400 cfm or 600 fpm)	20" × 24" × 12"	[b]

[a] "OPC and SMPS Efficiency Test Report, StrionAir ElectroFilter," Research Triangle Institute. The report was provided by StrionAir.

[b] Cost data are not available.

4.3.2.3 Technology Maturity for Use in the Advanced Filter. Two commercial EEF systems were identified in the market survey. The performance data of the two systems were requested from the manufacturers and are compared in Table 6. The StrionAir filter (with dimensions of 20" × 24" × 12") was tested by Research Triangle Institute using the ASHRAE Standard 52.2. The dust-loading test results, however, were not provided by the manufacturer because of the degradation due to the electric current increase. An initial collection efficiency of 95% for 1-µm aerosol was measured. The initial pressure drop at 500 fpm was 0.43 in. H_2O.

As shown in Table 6, better performances are claimed for the Technovation filtration system, which demonstrates HEPA collection efficiency and 0.5 in. H_2O pressure drop at 600 fpm. However, the current Technovation products are developed for clean room application rather than HVAC filtration.

Comparing the performance data presented in Tables 5 and 6, it was found that the collection efficiency (for 1-µm aerosol) and pressure drop of the EEF systems are equivalent to those reported for the high-efficiency electret filters. The advantage of an EEF system is that the filter system is claimed to be bactericidal, due to the combination effects of ionization, oxidative stress, and current flow across the filter media.

Battelle contacted Mr. Rex Coppom, Chief Technology Officer at StrionAir, to discuss the performance and cost of StrionAir's EEF filtration system. According to Mr. Coppom, the MERV 15 performance cannot be sustained when the EEF is tested following the ASHRAE Standard 52.2 method. Because 20% of the ASHRAE test dust (the Arizona Road Dust) is conductive, an increase in electric current through the filter element occurred during the dust loading, which automatically reduced voltage and subsequently, efficiency. Currently, it is not known whether the high conductivity of ASHRAE dust reasonably represents the conductivity of ambient aerosol because no literature was found reporting the conductivity of ambient aerosol (Hanley and Owen, 2003).

StrionAir stated that they are working to improve the EEF unit to overcome the problem and some progress has been made. The revised version of design will be submitted for retesting by LMS and Research Triangle Institute.

The initial cost for the StrionAir EEF system is $800 per 2,000 cfm of air capacity, which is more than 3.5 times the cost of uncharged high-efficiency filters and more than 5 times the cost of the high-efficiency electret filters presented in Table 2. The cost for the disposable filter, which must be changed every 6 to 12 months on average, is $95 for 2,000 cfm of air capacity.

Generally, an EEF system is much more expensive than an electret filter system considering the high initial cost and the additional costs of installation, maintenance, and operation. Degradation with loading is the other major drawback with the current version of the technology that prevents it from providing steady high-collection efficiency. Therefore, the EEF technology was eliminated from further consideration in this study as the basis for an advanced filtration system.

4.3.3 Nanofiber Filter

4.3.3.1 Technology Description. Nanofiber filter media were developed to provide improved filtration efficiency for a wide range of particles (0.2 to 8 µm) without a substantial increase in pressure drop. "Nanofiber" generally refers to a fiber with a diameter of less than 1µm. Small fibers in the nanofiber range can improve filter efficiency in the interception and inertial impaction regimes, although smaller fiber size leads to higher pressure drop. However, a theoretical analysis conducted by Graham (2002) indicated that for a fiber size smaller than 0.5 µm, the effect of slip flow at the fiber surface can also lead to better filter efficiency and lower pressure drop. For air filtration application, small fiber sizes (0.2 to 0.3 µm) are desired.

4.3.3.2 Potential Drawbacks. While nanofiber media can offer excellent performance in efficiency and airflow resistance, like any other filtration media, they have limitations. Based on our discussion with the manufacturers in the field, nanofiber media are likely more expensive compared to ordinary fiber media, although the cost data are not available at this stage. In addition, due to the thinness of the nanofiber media, their dust-holding capacity (or service life) could be low, especially when compared to a conventional deep filter media.

4.3.3.3 Technology Maturity for Use in the Advanced Filter. The leading manufacturer of nanofiber air filtration media is the Donaldson Company, Inc. Donaldson makes polymeric nanofibers using a proprietary electrospinning process that was developed in the 1970s and has been enhanced since that time (Barris et al., 2004; Benson et al., 2004; Chung et al., 2004; Gillingham et al., 2004; Gogins and Weik, 2004). The Donaldson nanofibers are formed into a nanoweb, which is very thin — consisting of just a few nanofiber diameters thick. The thinness of the nanoweb provides high permeability; however, the nanoweb must be supported by a substrate material to establish mechanical properties for use in a filter.

At Donaldson, a variety of substrate materials have been selected to provide appropriate mechanical properties to allow pleating, filter fabrication, and durability in use. In many cases, substrates have been selected that resemble conventional filter materials to allow the use of conventional filter media pleating equipment. Donaldson has used nanoweb technology for a variety of air filtration applications. The Ultra-Web® filters are used in industrial air filtrations for dust collection, which demonstrates good cleanability by pulse-clean. The Spider-Web® filters are used in gas turbine filtration.

To study the feasibility of using the nanoweb media in HVAC filtration, a sample medium being developed at Donaldson for HVAC application was sent to Battelle for testing. The technical properties of the sample medium are summarized in Table 7.

Table 7. Technical Properties of Donaldson Nanoweb Media (Grade 1291-20X)[a]

Construction	Polyamide nanofibers on a corrugated cellulose/synthetic blend
Basis Weight	120 g/m^2
Corrugation[b]	0.013 in.
Frazier Permeability[c]	0.5 in. H_2O @ 125 fpm
Efficiency	40% on a 0.76 µm PSL particle at 20 fpm
Maximum Operating Temperature	200 °F

[a] All properties presented in this table were provided by Donaldson Company, Inc.

[b] Filter media thickness.

[c] The measurement of the number of cubic feet of air per minute to pass through a square foot of filter media at a pressure drop of 0.5 in. of water.

As shown in Table 7, the collection efficiency of the sample media (as reported by the manufacturer) is significantly lower than our performance requirement of 99.9% efficiency.

Freudenberg is another manufacturer identified in the market survey as developing nanofiber filter media for air filtration application. According to Dr. Manz from Freudenberg, the nanofiber medium being developed at Freudenberg for HVAC filtration application has the potential to meet the performance goals of the advanced filter.

The nanofiber filter technology is still at the early stage of development for HVAC application. Discussions with the two major manufacturers in the nano-media area (Donaldson and Freudenberg) revealed that the performance goals may be achievable with the technology, but additional time and effort would be required. Nevertheless, it was determined that this technology shows sufficient promise and therefore warranted evaluation.

4.4 Summary of Literature Review

The performance requirements for the advanced filtration system were established as (a) efficiency higher than 99.9% for 1-µm aerosol and (b) pressure drop less than 0.5 in. H2O for a filter with dimensions not larger than 24" × 24" × 12" to handle 2,000 cfm of airflow.

Electret media were selected as the leading candidate technology to be further evaluated experimentally. The evaluation of the electret technology would focus on identifying the minimum collection efficiency using the method developed by Hanley and Owen (2003).

Samples of the nanofiber media would be experimentally evaluated to determine the feasibility of improving the nanofiber media to meet the advanced filtration system performance requirements. The EEF system was not selected as a candidate technology to be further evaluated because of its relatively high cost and the increase in electric current with dust loading (causing diminished collection efficiency).

5.0
Candidate Media Evaluation Tests

Eleven candidate media (8 electret and 3 nanofiber media) were obtained from manufacturers noted in Section 4.0 for initial assessment as to whether they would merit consideration for use in an advanced filter. The sample media were first tested for airflow resistance and initial aerosol collection efficiency (or initial penetration fraction). The sample media were cut into 47-mm diameter circular swatches and tested in modified commercial 47 mm diameter filter holders (BGI, Inc.).

Quality factors were calculated for each filter medium based on the results in airflow resistance and initial aerosol collection efficiency (details are provided in Section 5.3). The media with quality factors greater than the performance goal were selected for further testing to determine collection efficiency stability. In this test, the test media were conditioned with a nanometer-sized KCl aerosol in a laboratory or exposed to an indoor aerosol, as recommended by Hanley and Owen (2003), followed by collection efficiency measurement.

Detailed methods and procedures for airflow resistance measurement, aerosol collection efficiency measurement, laboratory conditioning, and ambient aerosol conditioning are described in Section 5.1. Results of the assessment are discussed in Section 5.2

5.1 Test Methods and Procedures

5.1.1 Airflow Resistance

The airflow resistance test system is illustrated in Figure 1. Room air was pulled through the test medium with a vacuum pump at flow rates corresponding to velocities ranging from 0 to 15 cm/s. The airflow resistance across the medium was measured with an inclined manometer.

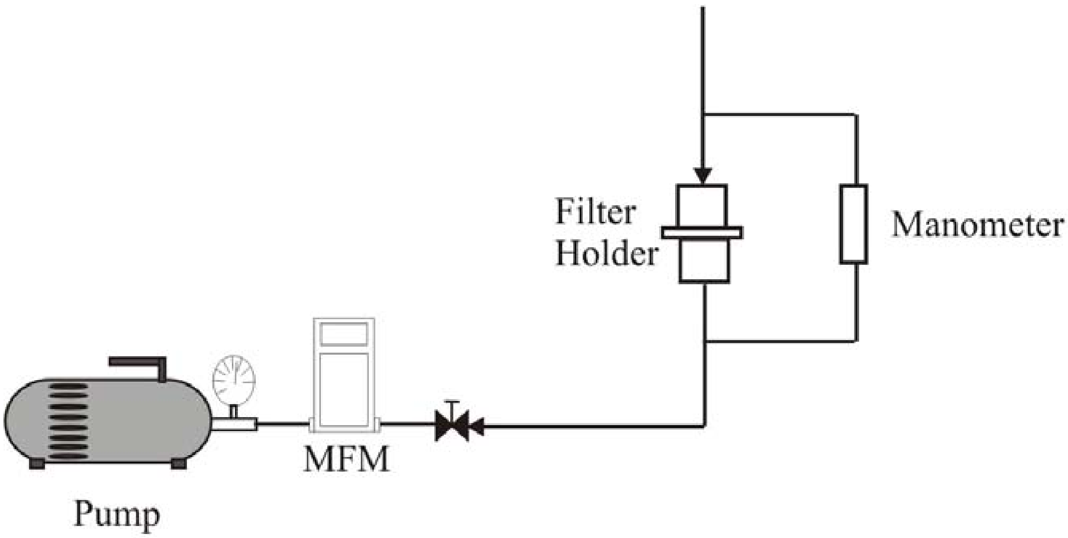
Measurements were first made after increasing the face velocity from 0 to 15 cm/s and then after decreasing the face velocity from 15 to 0 cm/s. The average of the two readings was recorded. A test was also performed at the same range of face velocities to measure the system pressure drop without the test media installed in the filter holder. Subtracting the system pressure drop from those with the test media in line yielded the net airflow resistance.

5.1.2 Aerosol Collection Efficiency

A schematic of the aerosol efficiency test system is shown in Figure 2, which consisted of a Collison nebulizer, a Kr-85 neutralizer (Model No. 3012, TSI Inc.), a Climet CI-500 laser particle counter (Climet Instruments Company), a vacuum pump, a modified 47-mm filter holder, and mass flow meters.

The Climet CI-500 is designed to detect light scattered by aerosol particles as they pass through the measuring volume defined by the width of the instrument's laser beam. To ensure that only one particle passes through the measuring volume at a time, the CI-500 has an upper detection limit of only up to 10^7 particles/ft^3 (350 particles/cm^3). This, however, did not introduce an aerosol counting problem because the instrument samples the aerosol at a relatively high airflow rate of 2.83 L/min, and its sampling time was set to one minute. The size range of the instrument is 0.3 to 10 μm, which is broken down into 5 size channels. The data collected were stored in the unit's internal memory during the test, after which, they were downloaded into Excel,® using the software provided with the instrument.

Figure 1. Schematic of the Airflow Resistance Test System



The nebulizer generated KCl aerosol in a range of 0.3 to 10 µm. The aerosol stream from the generator passed through a Kr-85 neutralizer. Upon exiting the neutralizer, a portion of the aerosol stream was pulled through the test filter by a vacuum pump. The remaining aerosol stream was vented.

During the efficiency test, the Climet CI-500 laser particle counter was used to size and count the number of particles upstream and downstream of the test filter media. The ratio of the downstream counts to the upstream counts was used to compute the fractional filtration efficiency for each of the particle size channels.

The tests were performed with a single layer of the test medium at velocities of 6.8, 10.2, and 13.6 cm/s. These three velocities correspond to 2,000 cfm of air flowing through media areas of 150, 100, and 75 ft^2, respectively, which cover the typical media areas in a 12-inch (30 cm) deep pleated commercial high-efficiency HVAC filter. After initiating the aerosol challenge at 6.8 cm/s, the particle counts in each size channel were recorded upstream for approximately 4 minutes. The particle counts were then recorded downstream for the next 4 minutes and then upstream again for another 4 minutes. This procedure was then repeated at 10.2 and 13.6 cm/s. Note that the challenge aerosol concentration was relatively stable during the test period, with typically less than 15% change in the upstream particle counts (for every channel) during a 15-minute testing time. To eliminate measurement error due to any unstable challenge concentration, at each test flow rate, upstream aerosol concentration was measured before and after every downstream concentration measurement. The average of the two upstream concentrations was then used with the downstream concentration to calculate the filter penetration.

To eliminate test system bias, background aerosol concentrations upstream and downstream of the test filter were measured at the beginning of each test with the aerosol generator turned off and with clean air flowing through the test filter at the testing flow rate. The penetration (p) was then calculated based on the ratio of the downstream to upstream particle concentrations corrected on a channel-by-channel basis as shown in Equation 1:

$$p = \frac{(C_D - C_{D_b})}{(C_U - C_{U_b})} \qquad (1)$$

where: C_D = Downstream particle count, particles/cm^3,
C_{Db} = Downstream background count, particles/cm^3,
C_U = Average upstream count, particles/cm^3, and
C_{Ub} = Average upstream background count, particles/cm^3.

The collection efficiency η was then computed, as shown in Equation 2:

$$\eta\,(\%) = 100 \text{ x } (1 - \text{p}) \qquad (2)$$

As illustrated in Figure 2, aerosol concentration was measured with the Climet CI-500, using identical sampling probes positioned upstream and downstream of the filter holder. The sampling ports were located approximately 5 cm from the filter holder on the 1.2-cm diameter inlet and outlet tubes.

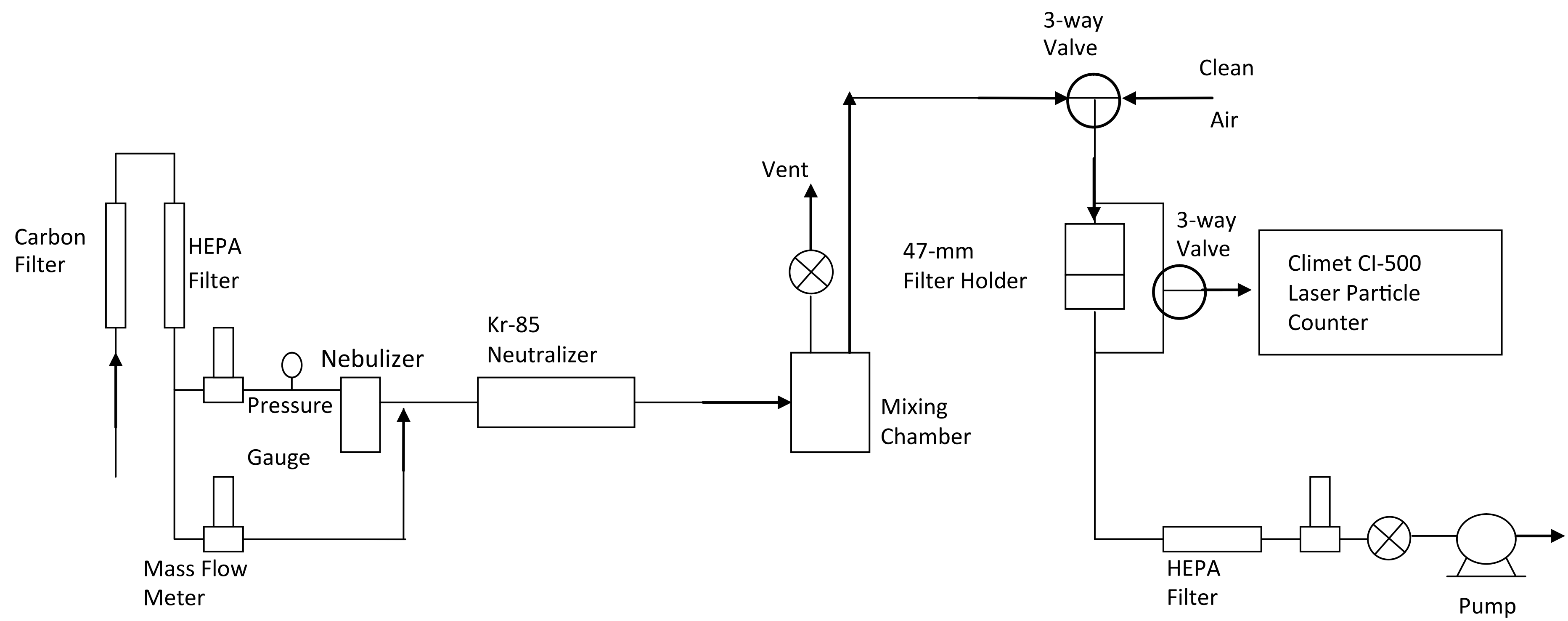
Note that some percentage of particle loss (especially for larger particles) through a sampling probe is inevitable in sampling probe design. However, as illustrated in Equation 3, the measured filter efficiency can be corrected if the particle deposition efficiencies through the sampling probes are known.

$$\textit{Filter Collection Efficiency}\,(\%) = \frac{\left[\dfrac{\textit{Measured Downstream Conc.}}{(1-\eta_{dep\_downstream})}\right]}{\left[\dfrac{\textit{Measured Upstream Conc.}}{(1-\eta_{dep\_upstream})}\right]} \qquad (3)$$

where $\eta dep\_{downsstream}$ and $\eta_{dep\_upstream}$ are the particle deposition efficiencies through the downstream and the upstream sampling probes, respectively.

Using a pair of identical probes in each measurement eliminated the need to know the particle deposition efficiency; since the upstream and downstream deposition efficiencies are identical, they can be cancelled out from Equation 3.

Figure 2. Schematic of the Aerosol Efficiency Test Setup



5.1.3 Laboratory Conditioning and Efficiency Evaluation

The laboratory conditioning was conducted using the conditioning procedure described by Hanley and Owen (2003). Hanley and Owen's study was supported by ASHRAE to establish a laboratory conditioning method to identify the minimum efficiency of electret filters in actual use. At the time of conducting this study, the conditioning method developed by Hanley and Owen was in public review and is to be included as an addendum to ASHRAE 52.2 for electret media evaluation.

The conditioning aerosol was generated using a Collison nebulizer. The nebulizer was operated with an aqueous solution of 0.03% KCl. The number concentration of the conditioning aerosol was monitored with a PORTACOUNT® condensation nucleus counter (TSI Inc., Shoreview, MN). Particles entering the PORTACOUNT® pass through a saturator tube where they are combined with alcohol vapor. They then pass into a condenser tube where alcohol condenses on them, causing each particle to grow into a larger droplet. The droplets then pass through a focused laser beam, producing flashes of light that are sensed by a photodetector. The particle concentration is determined by counting the light flashes. The PORTACOUNT® performs sampling at a flow rate of 0.7 lpm. During the conditioning, the aerosol number concentration was kept below 1×10^6 particle/cm^3 to prevent excessive coagulation of the conditioning aerosol.

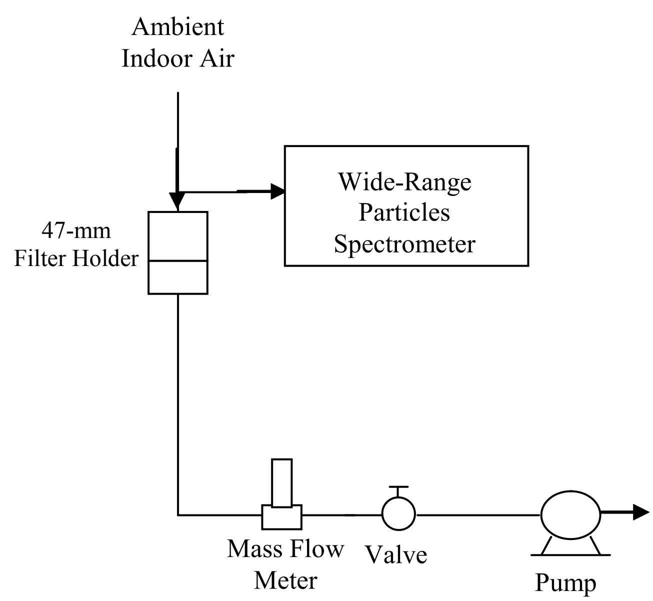
At the beginning of all tests, the size distribution of the laboratory conditioning aerosol was characterized with a Scanning Mobility Particle Sizer (SMPS, TSI Inc., Shoreview, MN). This instrument consists of an electrostatic classifier, which is used to separate particles by size, and a condensation particle counter, which counts the particles. The detection range of the instrument is 20 to 10^7 particles/cm^3. In the test configuration, this instrument had a sample rate of 0.3 L/min and a sample time of 2 minutes. The design of the instrument is such that the particles are counted one size channel at a time; thus, each size channel is sampled for only a fraction of the 2-minute sampling time. The effective range of particle diameters measured by the instrument was 0.015 to 0.66 µm. The SMPS was controlled by a computer, and all data were collected using the TSI's "Aerosol Instrument Manager" software. The data collected were then transferred to Excel,® using the "cut and paste" function, for further analysis. The size distribution was not monitored during the conditioning.

To identify the minimum efficiency of the electret sample, conditioning was performed in incremental steps with efficiency measured after each increment. A manifold consisting of six 47-mm filter holders was fabricated, and six sample swatches were conditioned each time. The collection efficiencies of the conditioned test media were then measured one at a time after each incremental conditioning step with 0.3 to 10 µm KCl aerosol at 10 cm/s. The 10 cm/s face velocity corresponded to 2,000 cfm air flowing through an overall media area of 100 ft^2. The efficiency measurement procedure was identical to that described in Section 5.1.2 except that the measurement was made at only one face velocity of 10 cm/s instead of three face velocities.

5.1.4 Ambient Conditioning and Efficiency Evaluation

As illustrated in Figure 3, the ambient conditioning test was conducted by exposing test medium to indoor aerosol at 10 cm/s in incremental steps. The collection efficiency of the conditioned media was measured after each incremental conditioning step with 0.3 to 10 µm KCl aerosol at 10 cm/s. At the beginning of the ambient exposure test, the size distribution of the indoor ambient aerosol was characterized with a Wide-Range Particle Spectrometer (WPS, Model 1000XP, MSP Corp. St. Paul, MN). The WPS is based on the same principle as that of the SMPS, with aerosol sizing and counting by laser light scattering, differential mobility analysis (DMA), and condensation particle counting (CPC). The detection range of the instrument is 20 to 10^7 particles/cm^3. In the test configuration, this instrument had a sample rate of 0.3 L/min. and a sample time of 1.6 min. The effective range of particle diameters measured by the instrument was 0.015 to 0.5 µm. The WPS was controlled by a computer, and all data were collected using the manufacturer-provided software.

Figure 3. Schematic of the Ambient Conditioning Test Setup



The instruments and equipment used in the test were calibrated according to the manufacturer's recommendations or on an annual basis. All digital flow meters were calibrated by the Battelle Instrument Lab following standard procedures. The particle-counting instruments, including Climet CI500, SMPS, PORTACOUNT®, and WPS, were calibrated according to the recommended instrument calibration frequencies and procedures provided in the respective manufacturer's manuals. All tests were conducted at ambient temperature and relative humidity. The particle-counting instruments were used within the detection limit of

Table 8. Test Matrix

Media Type	Media ID	Number of Tests			
		Airflow Resistance (0 ~ 16 cm/s)	Initial Penetration (@ 6.8, 10, 13.5 cm/s)	Laboratory Conditioning	Ambient Conditioning
Electret Media	A	2	2	2	-
	B	2	2	-[a]	-
	C	2	2	-	-
	D	2	2	-	-
	E	2	2	-	-
	F	2	2	2	-
	G	2	2	5	2
	H	2	2	-	-
Nanofiber Media	I	2	2	-	-
	J	2	2	-	-
	K	2	2	-	-

[a] Test was not conducted at the condition.

particle concentrations recommended by the manufacturers to ensure the calibrated precisions were achieved.

5.2 Test Results and Discussions

Tests were conducted to evaluate the airflow resistance and initial particle penetration of all candidate media. The top three media (all electret) were then further evaluated for efficiency stability after conditioning in laboratory or indoor ambient air. The test matrix is presented in Table 8.

The test results are presented in Sections 5.2.1 to 5.2.5 for airflow resistance, initial penetration fraction, quality factor, laboratory conditioning, and ambient conditioning, respectively. The sample media are designated as Samples A through K. To comply with the non-disclosure requirements from some media manufacturers, no further identification regarding media manufacturer, media type, or media properties is provided.

5.2.1 Airflow Resistance

The initial airflow resistances of the candidate media were measured at velocities ranging from 0 to 15 cm/s. Figures 4 and 5 present the results of the electret media and nanofiber media, respectively. Duplicate tests were conducted for each candidate material. The pressure drops plotted in Figures 4 and 5 are the average of the two tests; the error bars provide the range of the two measurements.

As expected, the pressure drop increased linearly with velocity in the range of velocities studied. As the velocity increased from 6.8 to 13.5 cm/s (equivalent to reducing the design media area of a 2,000-cfm filter from 150 to 75 ft^2), the airflow resistance increased by approximately a factor of two for all sample media tested.

Figure 4. The Initial Airflow Resistance of Candidate Electret Media

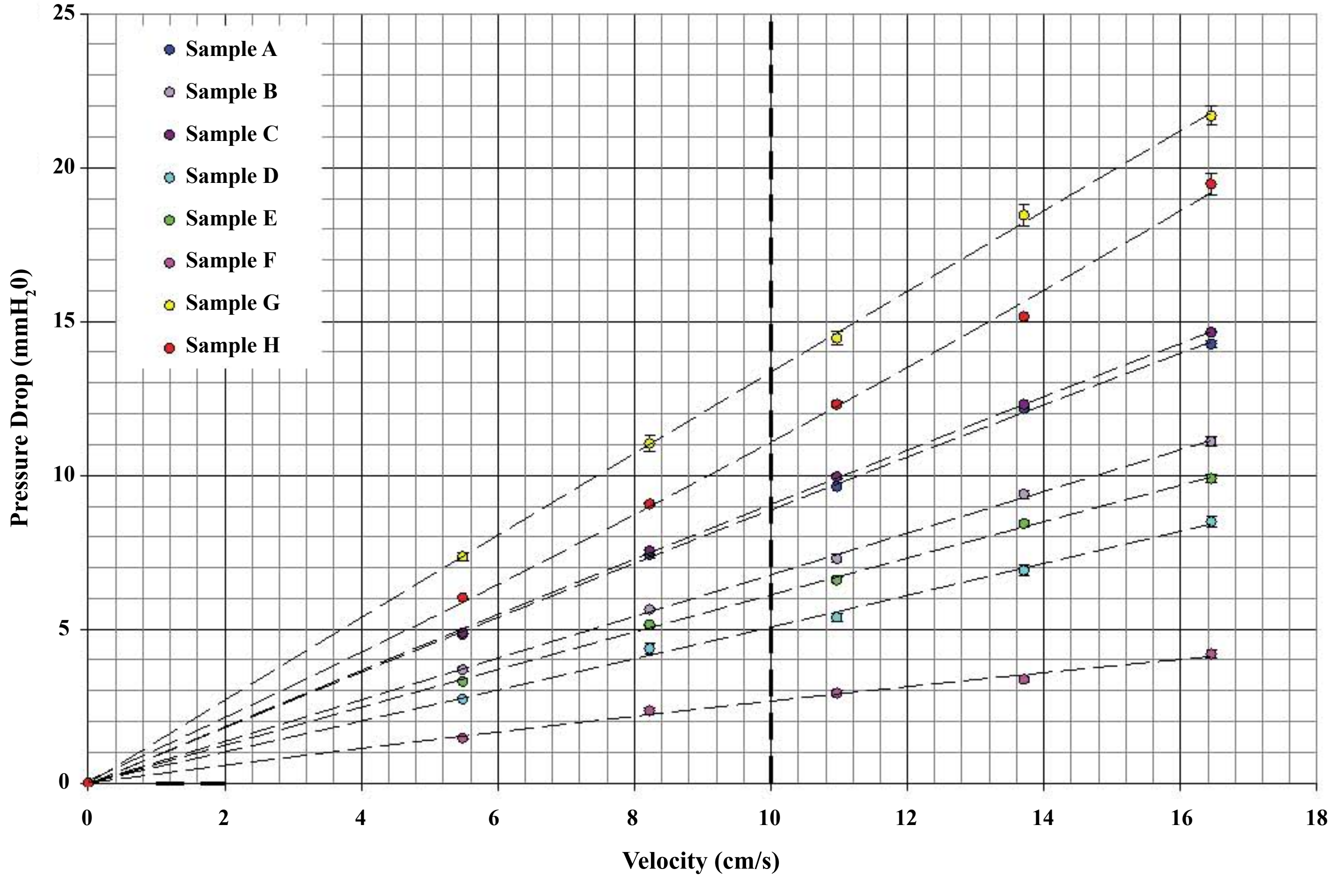
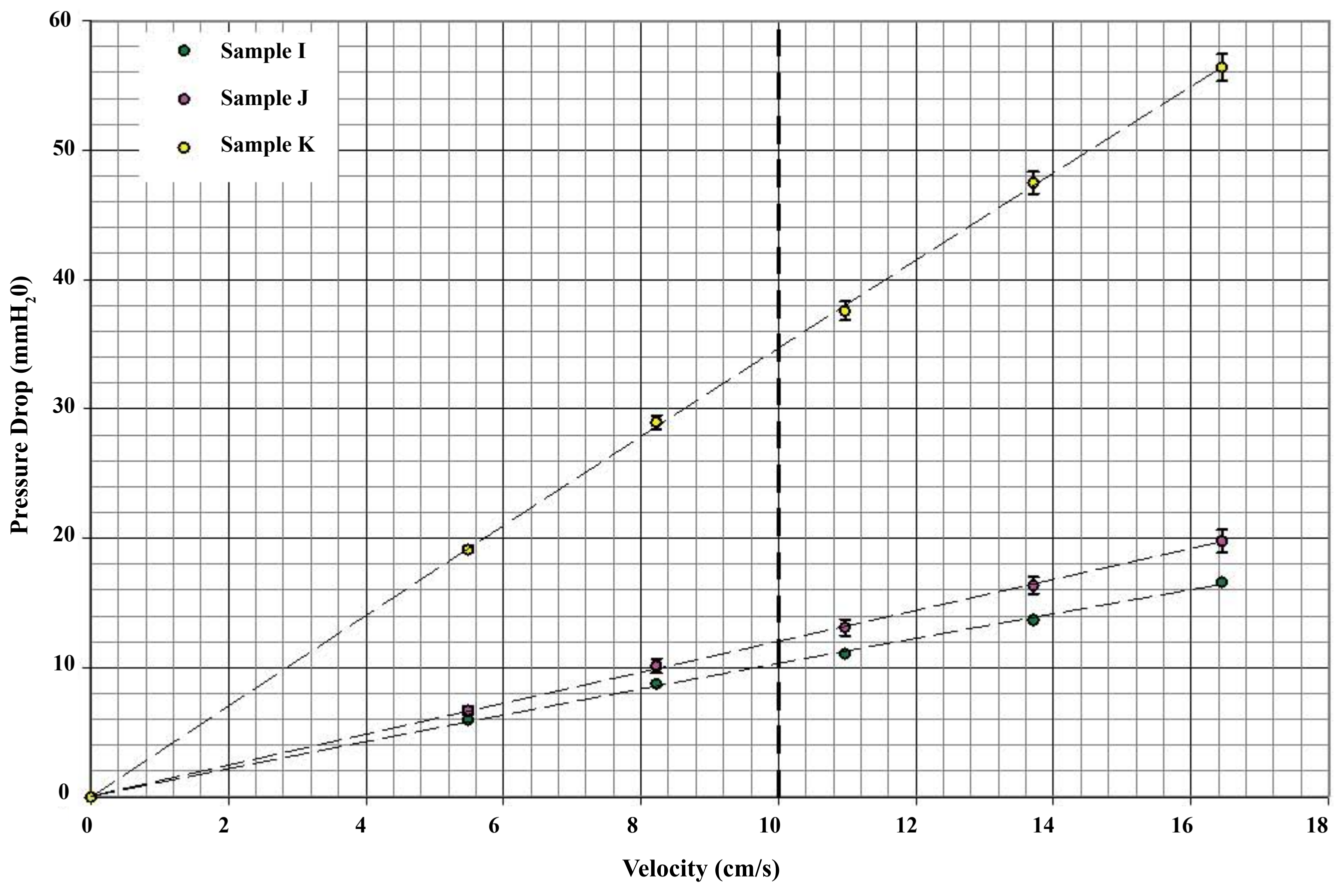


Figure 5. The Initial Airflow Resistance of Candidate Nanofiber Media



5.2.2 Initial Penetration Fraction

The initial penetration fractions of the electret candidate media at 10 cm/s are compared in Figure 6. As expected, the penetration fraction decreased as the particle diameter increased. For different electret, the measured penetration fraction varied within a large range. For example, at 0.75 µm, the measured penetration fraction ranged from 0.0001 for Sample G to 0.26 for Sample E. Similarly, as shown in Figure 7, the penetration fraction of the nanofiber media also increased as the particle size decreased. At 0.75 µm, the measured penetration fraction of the nanofiber media ranged from 0.0005 for Sample K to 0.13 for Sample I.

Figure 6. Initial Penetration Fraction of Electret Candidate Media

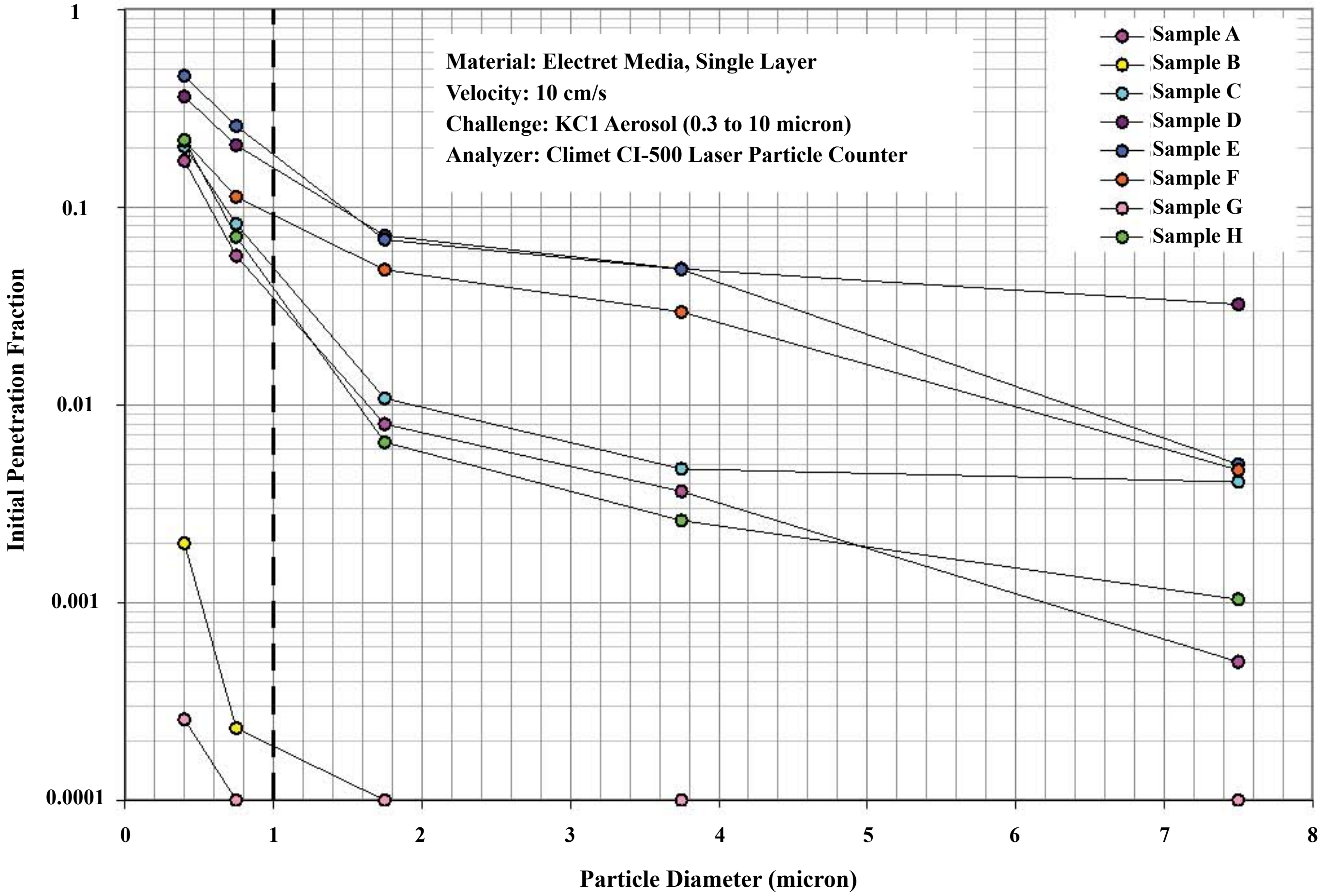
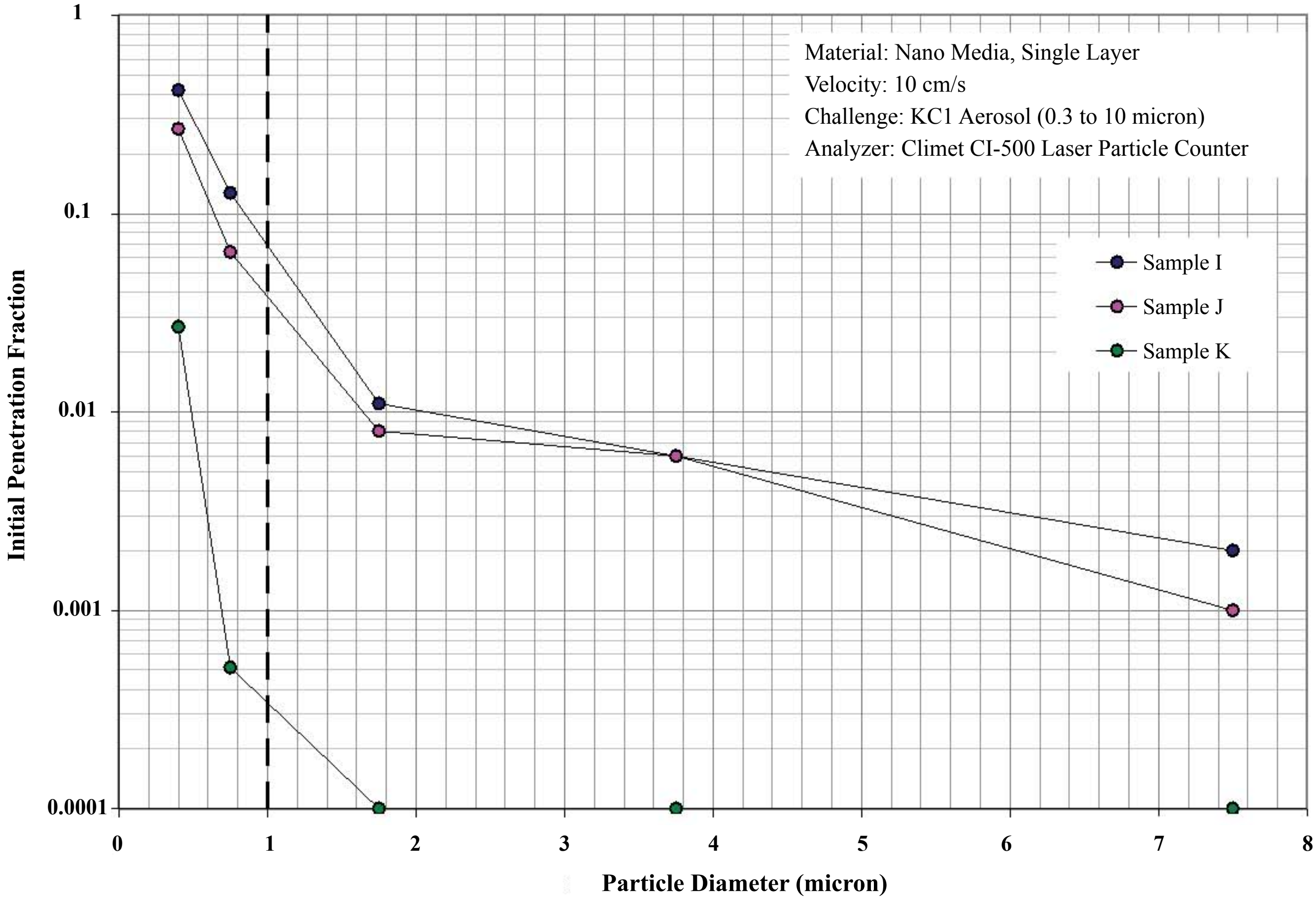


Figure 7. Initial Penetration Fraction of Nanofiber Candidate Media



To investigate the effect of velocity on collection efficiency, the initial efficiency of the candidate media was also measured at two other velocities (6.8 and 13.5 cm/s). The results are presented in Figure 8. As shown in Figure 8, the effect of velocity on initial penetration of 1-µm particles is not significant. For all candidate media tested, when the velocity increased from 6.8 to 13.5 cm/s, the change in efficiency of 1-µm particles was less than 7%. Therefore, increasing media area in a filter design can effectively reduce pressure drop; however, its benefit to collection efficiency is limited, within the range of velocities tested.

Figure 8. Initial Collection Efficiency of Candidate Media at Varying Velocities

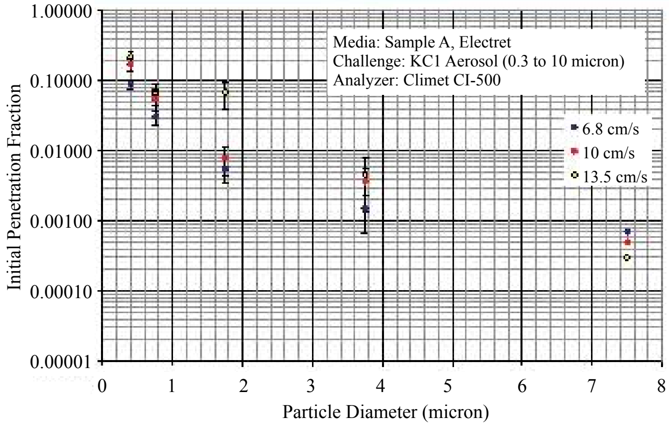


Figure 8a. Sample A

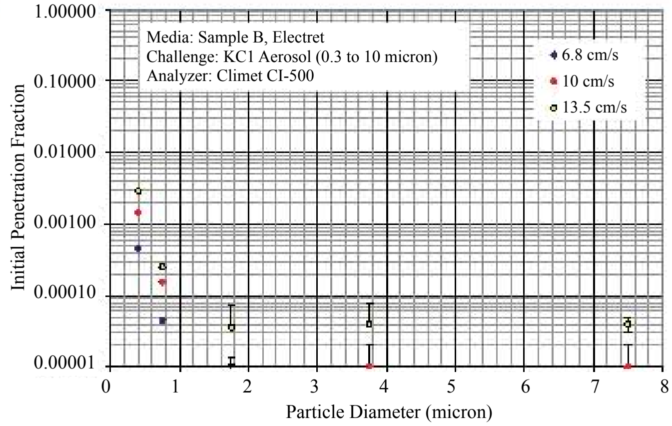


Figure 8b. Sample B

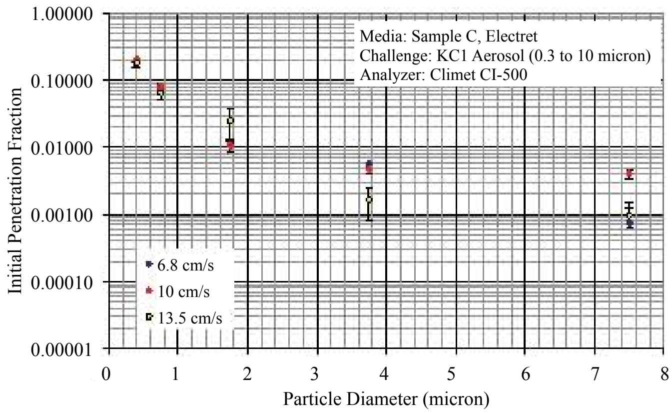


Figure 8c. Sample C

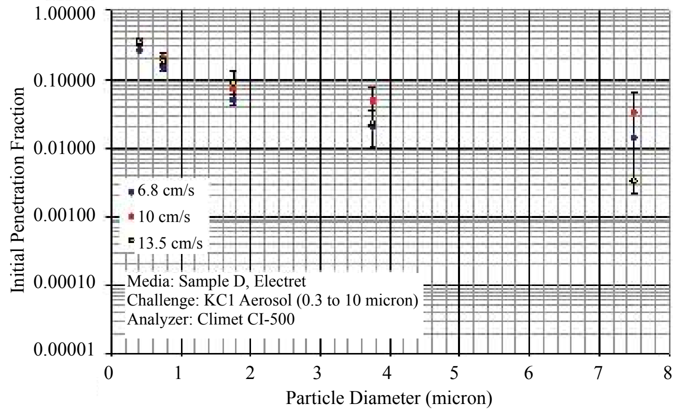


Figure 8d. Sample D

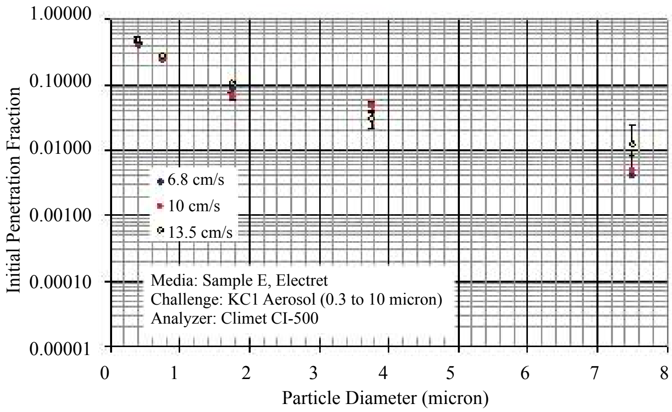


Figure 8e. Sample E

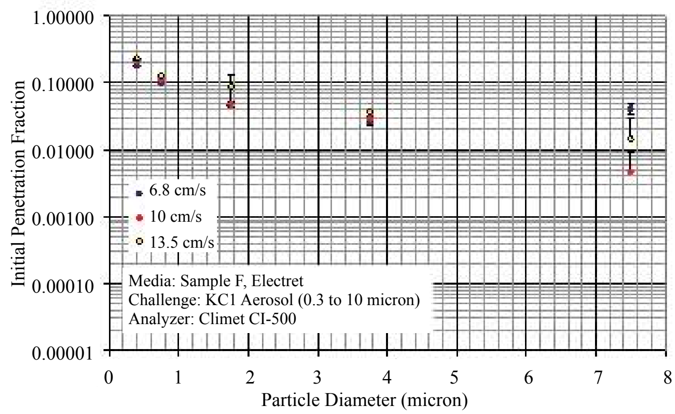


Figure 8f. Sample F

Figure 8. Initial Collection Efficiency of Candidate Media at Varying Velocities (Continued)

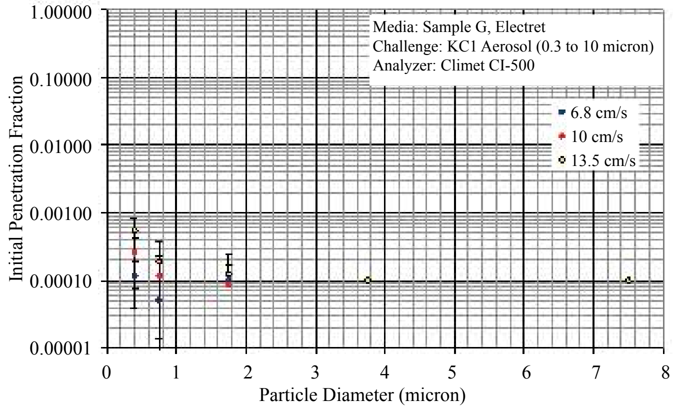


Figure 8f. Sample F

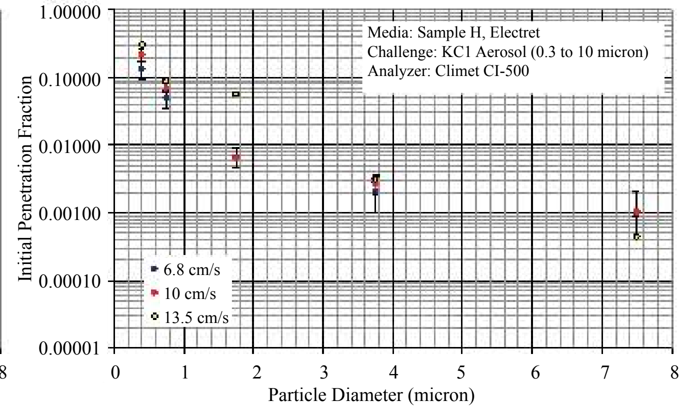


Figure 8h. Sample H

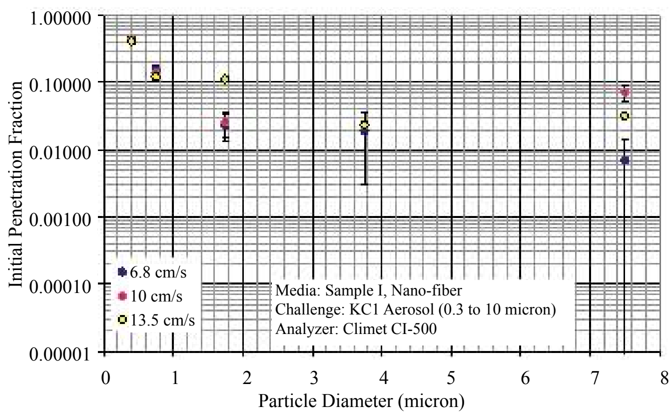


Figure 8i. Sample I

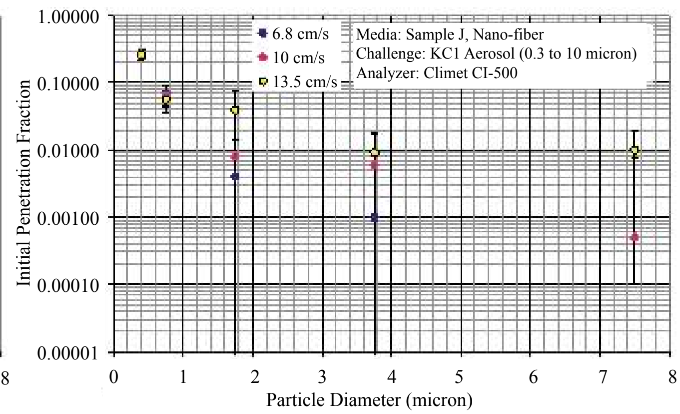


Figure 8j. Sample J

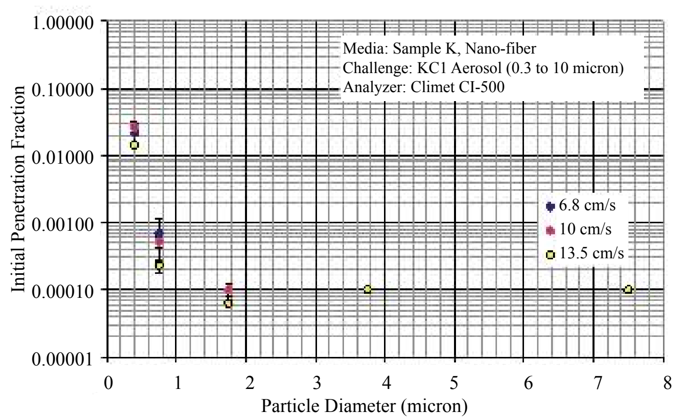


Figure 8k. Sample K

5.2.3 Quality Factor

To compare the overall performance of candidate media, a parameter designated as "quality factor" was introduced. As shown in Equation 4, the quality factor (QF) is defined as:

$$QF = \frac{(-\ln p)}{\Delta P \times \delta} \qquad (4)$$

where: p is the penetration fraction of 1-μm particles at 10 cm/s,
ΔP is the pressure drop (mmH_2O) at 10 cm/s, and
δ is the filter media thickness (mm).
Note: 25.4 mm = 1 inch

The filter media thickness (δ) was measured by Battelle. For each candidate media, three filter samples were measured. The average thickness was used in Equation 3 to calculate the QF. For a medium that meets the current performance goal, the QF is 0.54. Table 9 summarizes the QF, the initial penetration fraction, the initial airflow resistance, and the media thickness of all candidate media tested. For comparison, the target QF based on the performance goal is also presented in Table 9.

As shown in Table 9, all three nanofiber media (Samples I, J, and K) had QFs much lower than the target quality factor. With the QFs all lower than the baseline QF of 0.54, this indicates that any advantage the media has with regard to higher efficiency or lower pressure drop than the requirement is more than offset with a corresponding lower efficiency or higher pressure drop. Therefore, none of the nanofiber media were further evaluated for collection efficiency stability.

Among the eight candidate electret tested, only Samples A, F, and G have QFs higher than 0.54. This means that the media offer a combined increased efficiency or reduced pressure drop compared to the baseline requirement that is beneficial to overall filter performance. These three sample media were selected for further conditioning tests to evaluate their potential degradation with aerosol loading. Candidate media F and G are from the same manufacturer, and when the samples were provided, the manufacturer indicated that they could further engineer the media. Samples F and G were intended to bracket the target filtration efficiency and airflow resistance, with the intent that a medium could then be engineered to more closely meet target specifications.

5.2.4 Laboratory Conditioning

Based on the quality factor, the initial efficiency, and the airflow resistance, sample media A, F, and G (all electret technologies) were selected as the most promising media for further evaluation with laboratory aerosol conditioning.

At the beginning of the tests, the size distribution of the conditioning aerosol was characterized with a TSI Model 3080 Scanning Mobility Particle Sizer (SMPS, with TSI Model 3081 DMA and Model 3025 CPC). The SMPS operated at an impactor inlet diameter of 0.0457 cm, a sample flow rate of 0.3 lpm, a sheath flow rate of 3 lpm, and a size range from 15.1 to 661 nm. The results are presented in Figure 9. The challenge conditioning KCl aerosol is in solid-phase, with a particle density of 1.98 g/cm^3. The number mean diameter was approximately 34 nm, with a geometric standard deviation of approximately 1.55. The mass mean diameter was 67 nm. **Note:** Count mean diameter (CMD) which is shown on the graphs is synonymous with number mean diameter.

During the conditioning, the aerosol number concentration was measured periodically with a TSI Model 8020 PORTACOUNT®. The average number concentration was approximately 400,000 particles/cm3. The aerosol collection efficiencies of the sample media were measured after each conditioning stage. Duplicate tests were conducted for each candidate media. The average penetration fraction of the duplicate tests is presented in Figures 10, 11, and 12.

Table 9. Quality Factor Comparison of the Candidate Sample Media (At 10 cm/s for 1-μm particle)

Media Type	Sample I.D.	Quality Factor	ΔP (mmH_2O)	Penetration Fraction	Thickness (mm)
Electret Media	Sample A	0.59	8.9	0.044	0.6
	Sample B	0.27	6.8	0.0001	5.1
	Sample C	0.31	9.0	0.063	1
	Sample D	0.50	5.0	0.172	0.7
	Sample E	0.36	6.1	0.211	0.7
	Sample F	1.20	2.8	0.095	0.7
	Sample G	0.86	13.5	0.0001	0.8
	Sample H	0.44	11.0	0.055	0.6
Nano-Media	Sample I	0.22	10.1	0.11	1
	Sample J	0.26	12.0	0.059	0.9
	Sample K	0.26	34.8	0.0003	0.9
Performance Goal		**0.54**	**12.7**	**0.001**	**1**

Figure 9. Size Distribution of the Conditioning Aerosol (Measured by SMPS)

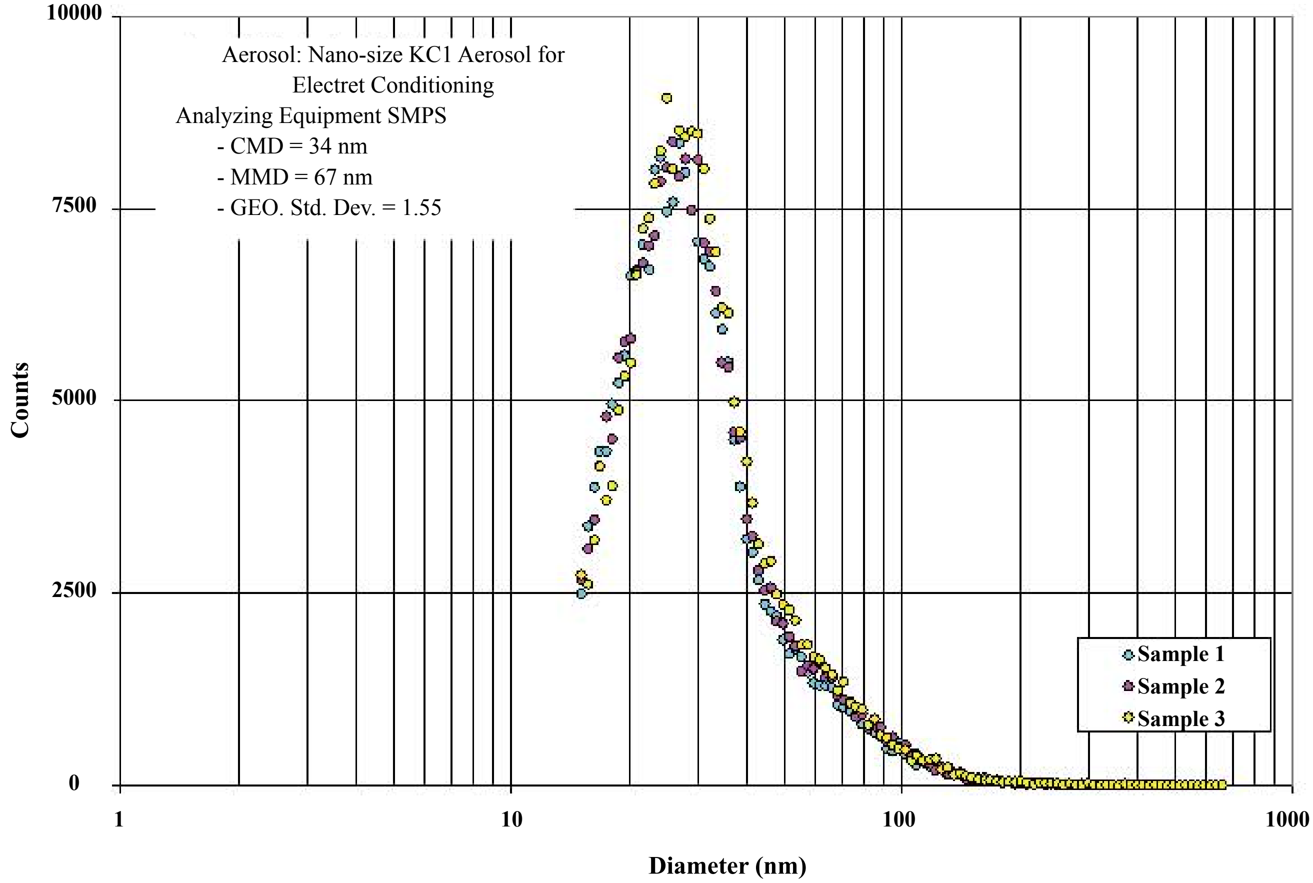


Figure 10. Incremental Laboratory Conditioning of Sample A Electret Media

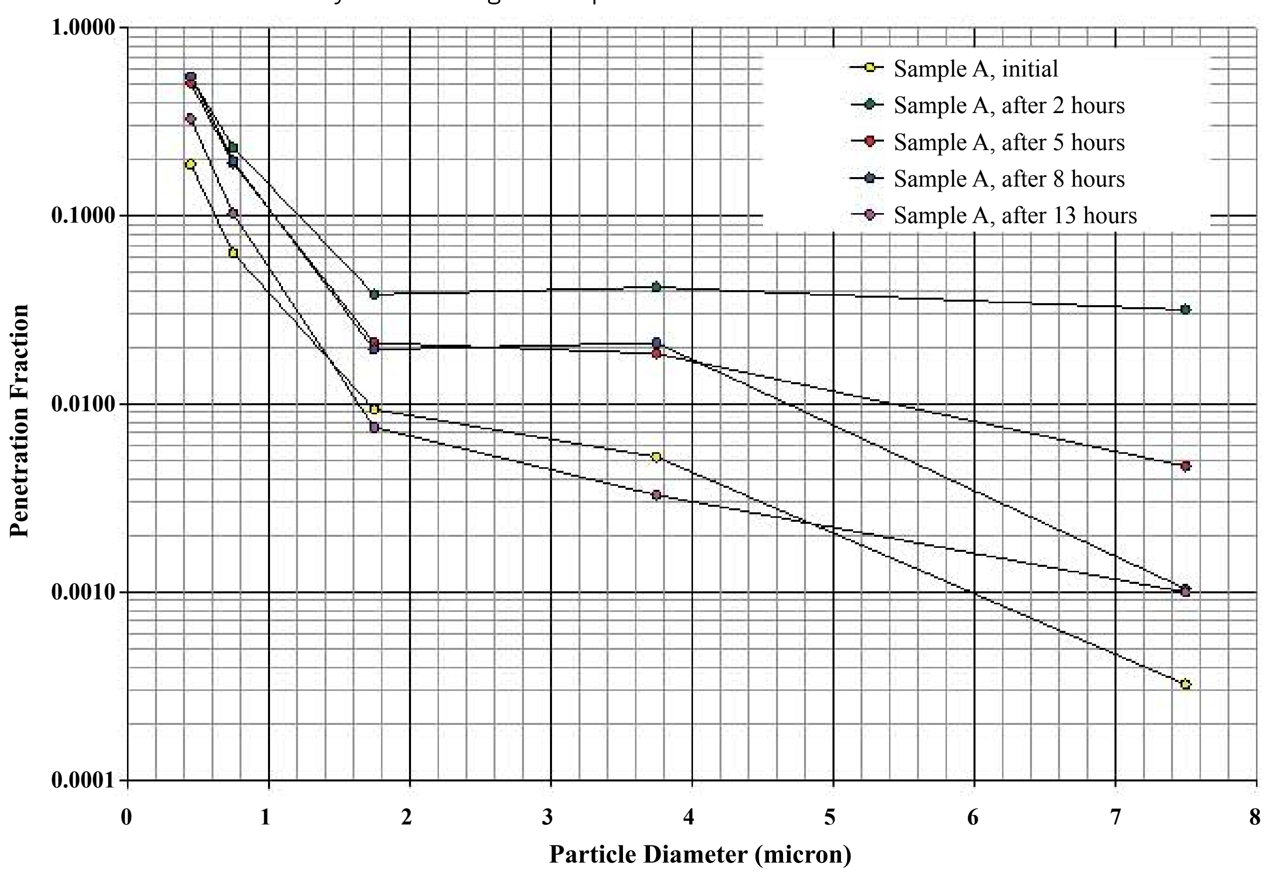


Figure 11. Incremental Laboratory Conditioning of Sample F Electret Media

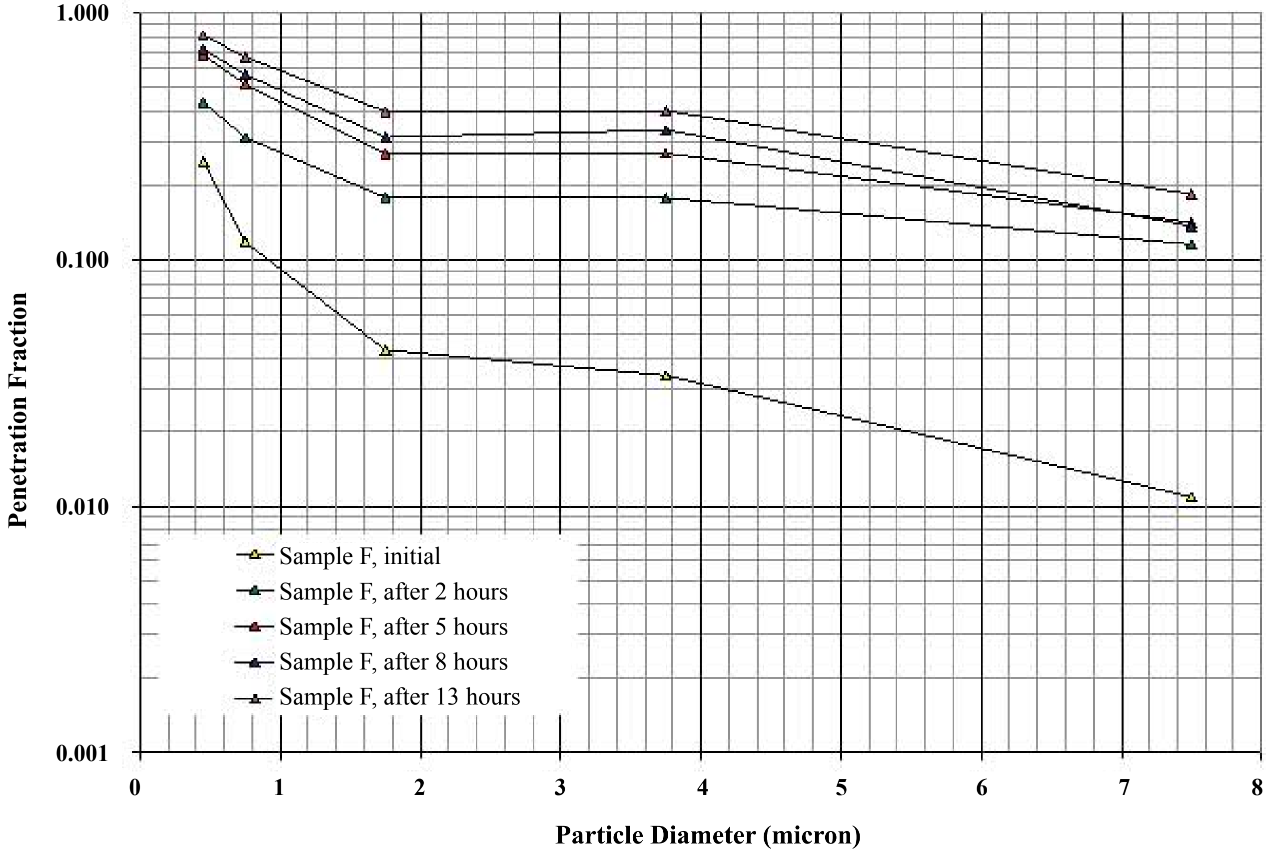
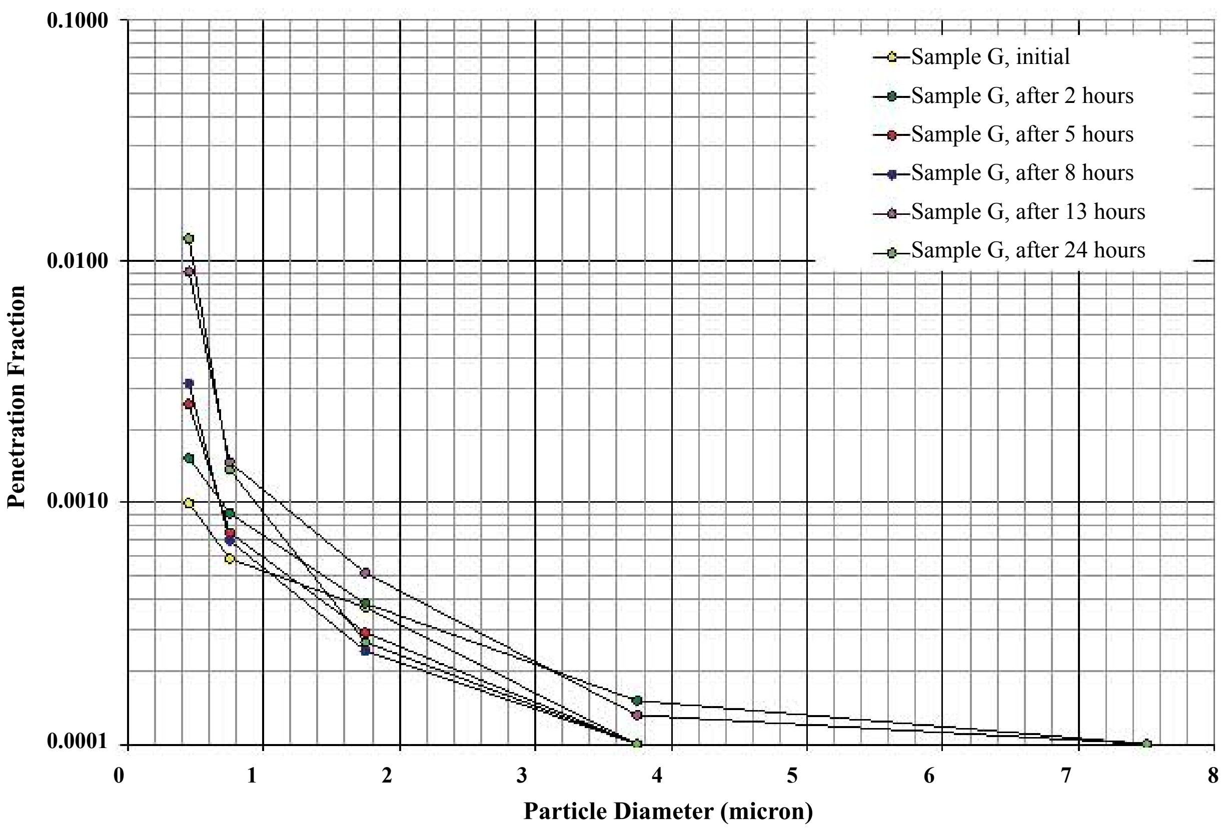


Figure 12. Incremental Laboratory Conditioning of Sample G Electret Media



As shown in Figure 10, Sample A degraded significantly during the first 2 hours of conditioning. At 0.75 µm, the penetration fraction increased from the initial 0.06 to 0.23 after 2 hours of conditioning. The penetration fraction then remained at 0.19 after 5 and 8 hours of conditioning, and reduced to 0.1 after 13 hours of conditioning, indicating the maximum penetration fraction of Sample A was approximately 0.23.

Sample F media degraded continuously during the 13 hours of conditioning. As shown in Figure 11, the penetration fraction at 0.75 µm increased from the initial 0.12 to 0.31, 0.51, 0.57, and 0.67 after 2, 5, 8, and 13 hours of conditioning, respectively. Compared to Samples A and F, Sample G demonstrated excellent stability in penetration fraction. The penetration fraction at 0.75 µm increased only 0.0013 from the initial 0.0001 to 0.0014 after 24 hours of conditioning.

To verify the penetration stability measured for Sample G, the laboratory conditioning test of Sample G was repeated. To identify the maximum penetration of Sample G media, the overall conditioning time was extended to beyond 24 hours. Triplicate tests were conducted. The average penetration fraction of the triplicate tests is presented in Figure 13.

Similar to that demonstrated in Figure 12, in the repeated test (see Figure 13), the reduction in penetration fraction was not significant after 35 hours of laboratory conditioning. The penetration fraction (the average of three sample swatches) as a function of time is presented in Figure 14, where the error bars illustrate the deviation of the individual sample from the average.

As shown in Figure 14, the penetration fraction reached its maximum penetrations of 0.013 and 0.0015 for 0.4 and 0.75 µm particles, respectively, after 15 hours of laboratory conditioning. Note that the minimum efficiency for 1-µm particles (interpolated using the efficiencies at 0.75 µm and 1.75 µm) just met the performance goal of not lower than 99.9%.

Figure 13. Incremental Laboratory Conditioning of Sample G Electret Media (Repeated Test)

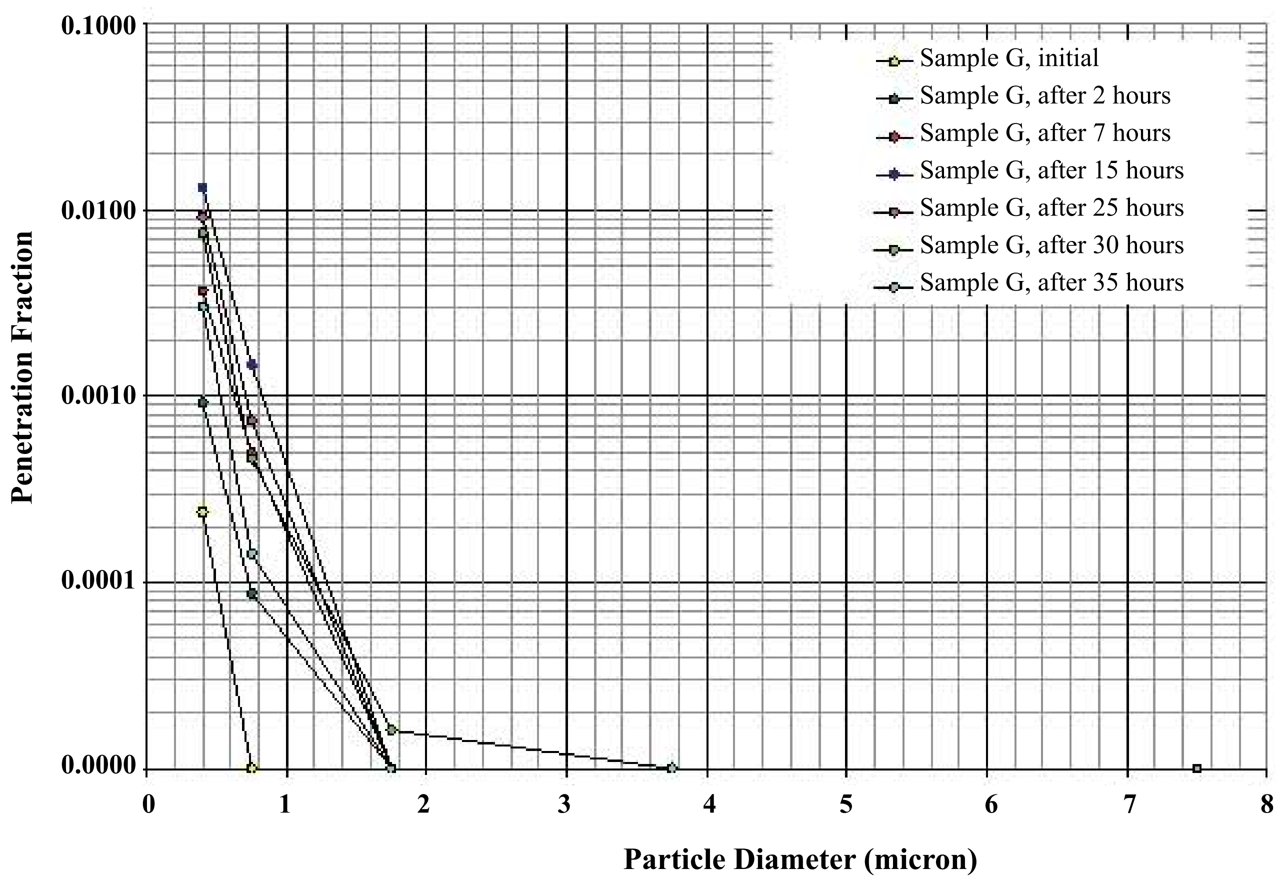
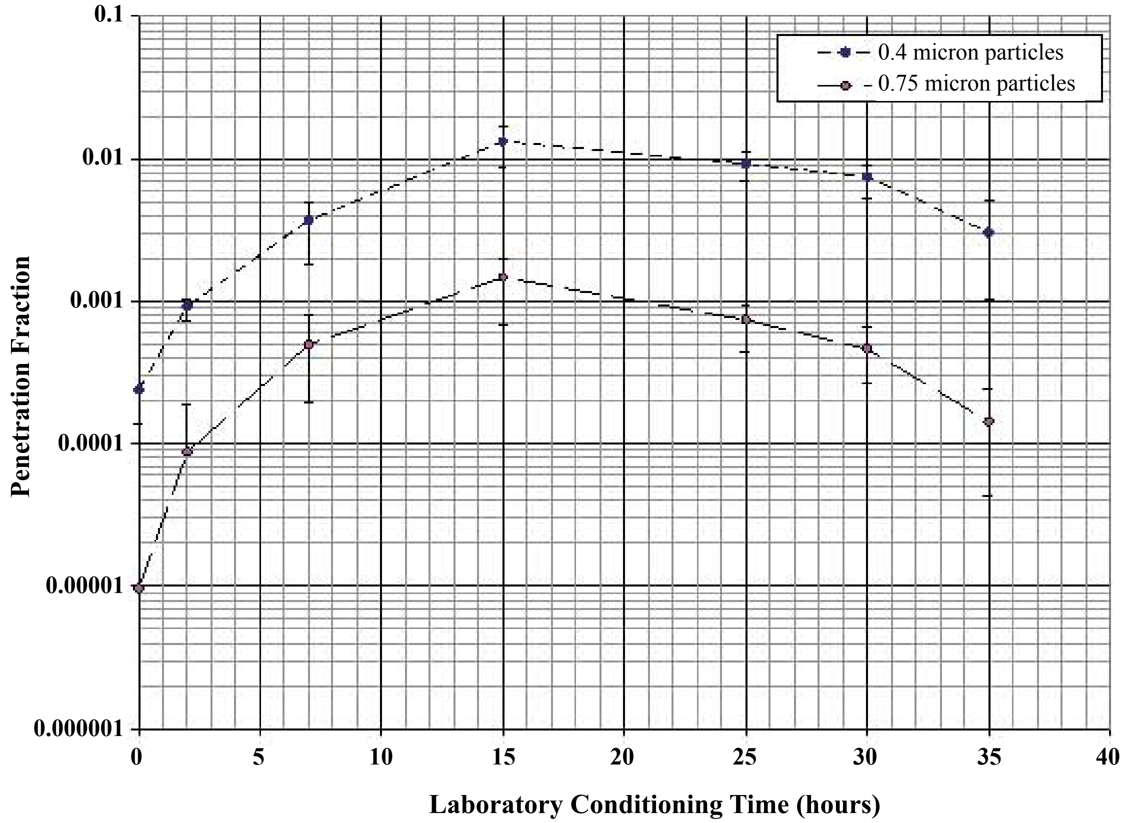
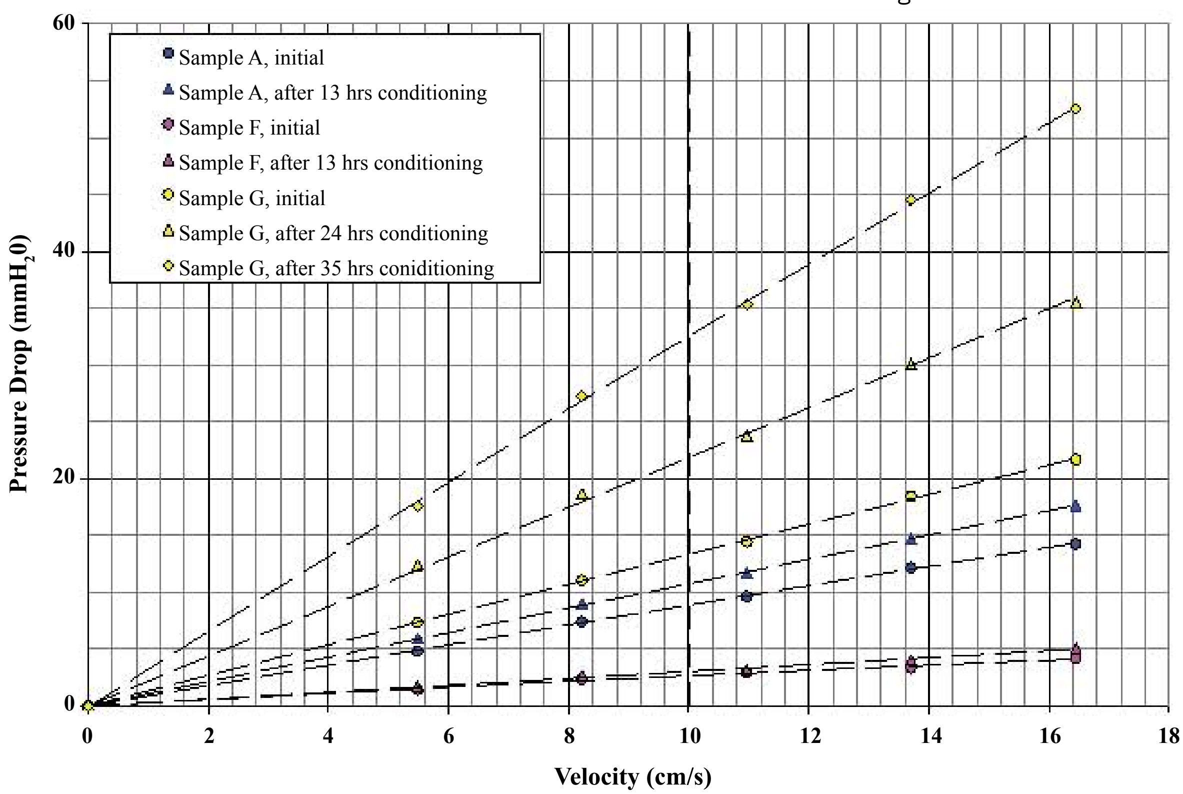


Figure 14. Penetration Fraction as a Function of Conditioning Time (for Sample G Electret Media)



The airflow resistances were measured after the final conditioning of the three candidate electret media. The results are presented in Figure 15. The airflow resistance of Sample G media more than doubled after 35 hours of laboratory conditioning, implying that the voids between electret fibers were reduced and the mechanical-collection mechanism became important.

Figure 15. The Airflow Resistance of Candidate Electret Before and After Conditioning



5.2.5 Ambient Conditioning

The laboratory conditioning tests presented in Section 5.2.4 identified Sample G as the most promising electret with the best stability in collection efficiency. As discussed in Section 4.3, the collection efficiency stability, which determines its minimum collection efficiency, is the most important parameter for assessing an electret filter medium. Electret media with higher efficiency stability would have a higher minimum collection efficiency when compared to an electret medium with the same initial efficiency but lower efficiency stability.

Sample G was tested further for efficiency stability with ambient conditioning. At the beginning of the ambient conditioning test, the size distribution of the indoor aerosol was characterized with a Wide-Range Particle Spectrometer (WPSTM, Model 1000XP, MSP Corp., St. Paul, MN). The WPS was selected to characterize the size distribution of the conditioning indoor aerosol because indoor aerosol contains a significant amount of fine particles at nano-size range and the WPS (like the SMPS) is able to detect particles with diameters down to 0.015 µm. Compared to SMPS, the WPS operates based on the same aerosol sizing and counting principles, and is able to detect the similar particle size range with the same detection limit in total particle concentration as that of the SMPS. Therefore, WPS is expected to provide equivalent results in size distribution and particle concentration to those of the SMPS. The results are presented in Figure 16. The number mean diameter was approximately 67.2 nm, with a geometric standard deviation of approximately 1.9. The mass mean diameter was 206 nm. The indoor aerosol distribution stability was not monitored during the long-term conditioning.

The aerosol number concentration was measured periodically with a TSI Model 8020 PORTACOUNT® during the ambient conditioning test. The average number concentration was approximately 13,300 particles/cm^3.

Duplicate samples were conditioned and the aerosol penetration of each was measured. The average penetration fraction measured is presented in Figure 17. As shown in Figure 17, after 16 and 34 days of ambient conditioning, the aerosol penetration fraction increased by factors of ~2 and ~4, respectively, for 0.75-µm particles. The penetration fraction increased 30% for 1.75-µm particles after 34 days of conditioning. The penetration at 1 µm met the performance goal of less than 0.001 during all tests. The penetration at 1 µm was interpolated using data at 0.75 and 1.75 µm, assuming the penetration fraction curve is approximately linear at particle diameters from 0.75 to 1.75 µm. This assumption of a pseudo-linear curve is reasonable, considering the relatively small interpolation interval in diameter.

Figure 16. Size Distribution of the Indoor Ambient Conditioning Aerosol (Measured by WPS)

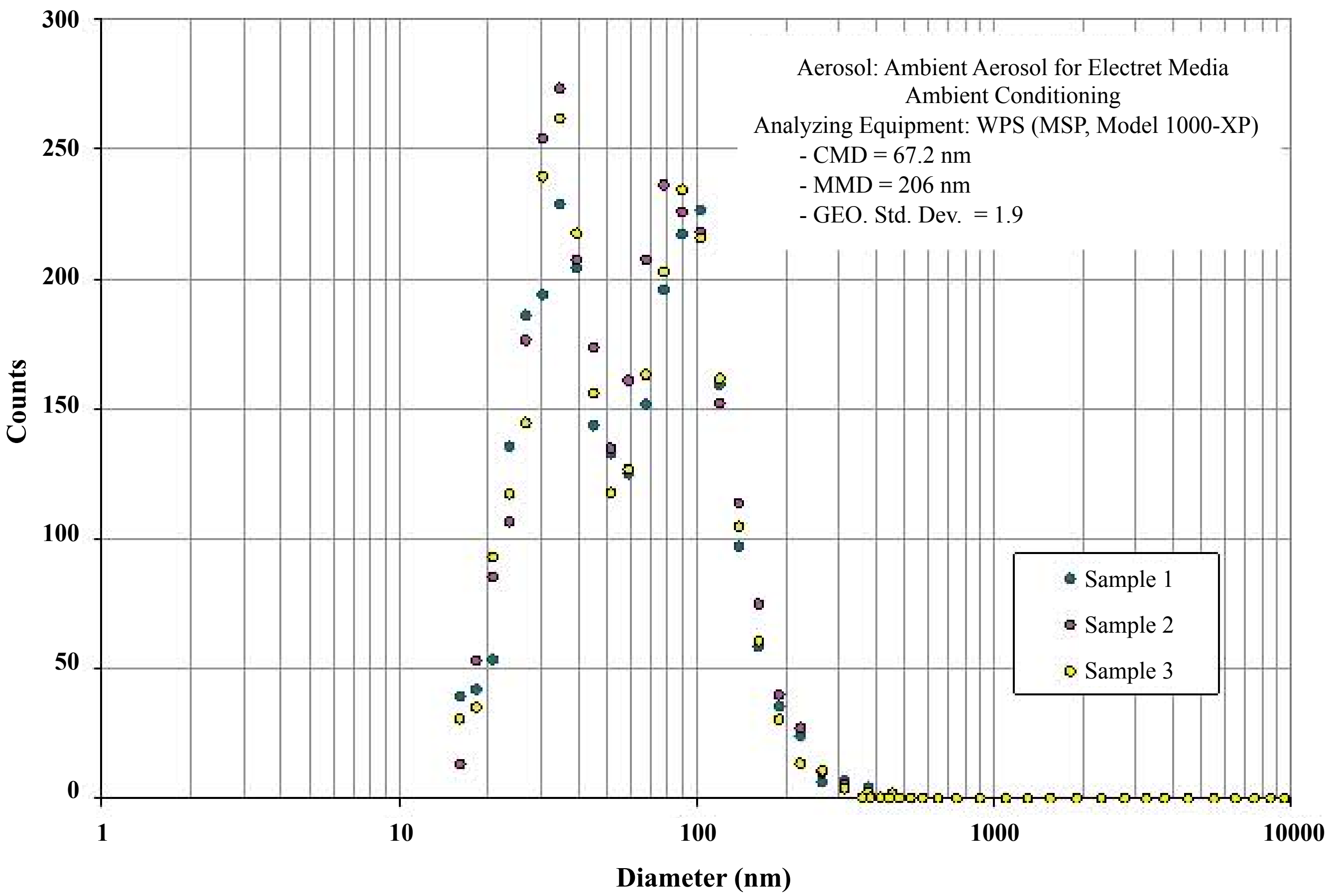
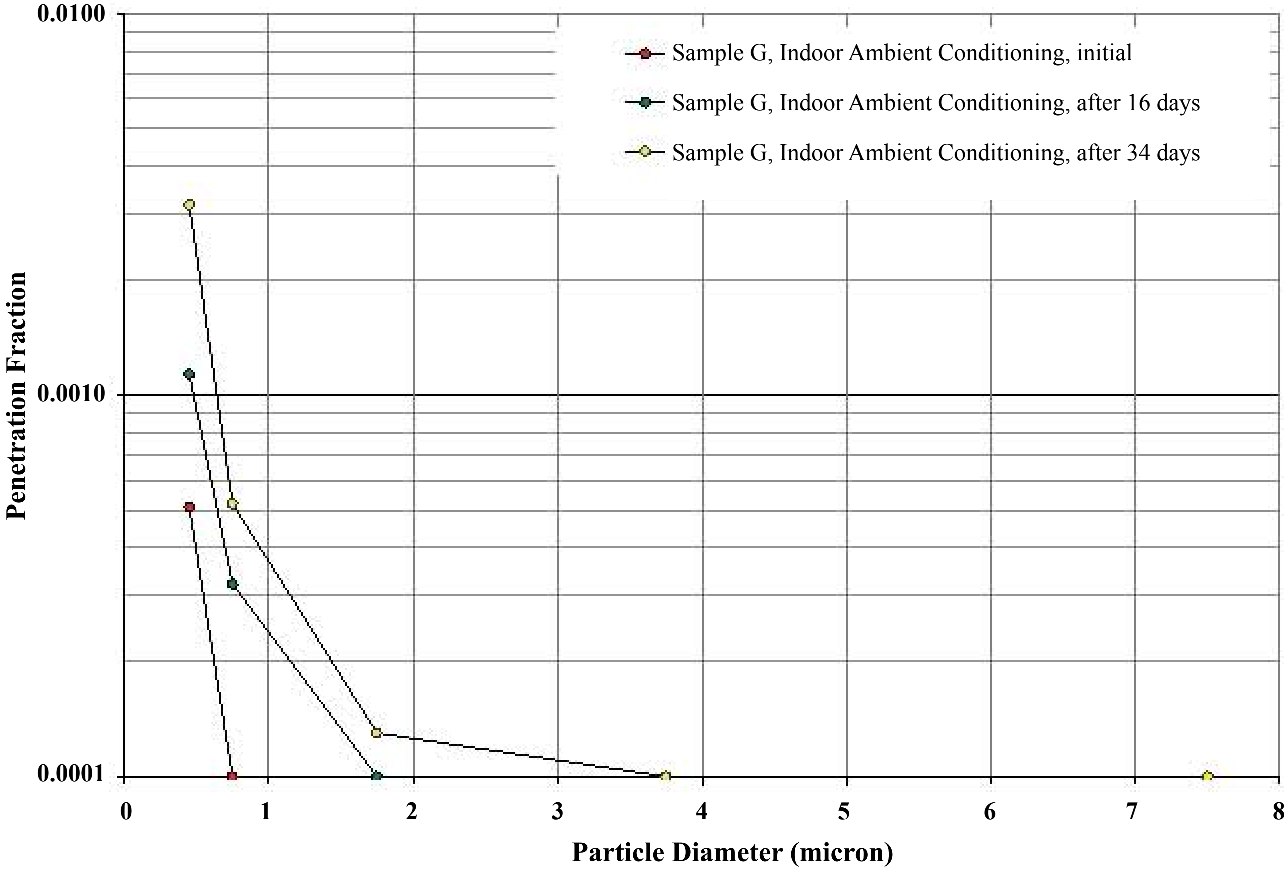


Figure 17. Indoor Ambient Conditioning of Sample G Electret Media



5.3 Summary of Experimental Study

Based on the screening tests (airflow resistance and initial collection efficiency) conducted with sample media from the candidate manufacturers, none of the nanofiber media met the performance goals of the supposed advanced filtration system.

One electret media, Sample G, demonstrated high potential to meet the performance goals. The initial and minimum collection efficiencies met the performance goal of ≥ 99.9% (penetration fraction of ≤ 0.001) for 1-µm diameter particles. The initial pressure drop of 0.53 in. H_2O was slightly higher (6% higher) than the requirement of the advanced filtration system. By enhancing the filter design area slightly (over 100 ft^2), the performance goal in airflow resistance could most likely be met.

The manufacturer of Sample G indicated they are developing a high-efficiency electret filter with a target performance of MERV 16. The new electret filter uses an improved electret media that has even better efficiency stability (over time) than Sample G. According to the manufacturer, the new electret filter is being tested and will be commercially available soon.

5.4 Advanced Filter Development

The original objective of the project discussed in this report was to develop an advanced filtration system and then assess its performance using the ASHRAE 52.2 test method. In review of the results presented in Sections 5.1 through 5.3 above, it was considered possible to develop a filter with better performance than that of filters currently on the market. It was determined, however, that the incremental gain in collection efficiency, along with the incremental reduction in airflow resistance, were not sufficient to merit continuing with the development of the advanced filter under this project. In addition, the decision to not proceed with developing the advanced filter in this project was also due to the fact that the manufacturer of the leading media assessed (Sample G) was already making further improvements to that material and a filter made of the improved media was expected to be on the market soon.

6.0 Conclusions and Recommendations

A literature search and market survey were conducted to identify candidate advanced filtration technologies that could be used as the starting point for further developing a filtration system that has a lower pressure drop than conventional high-efficiency particulate filters, with higher or equivalent collection efficiency and comparable or lower cost. As a result of the literature review and market survey, two technologies (electret and nanofiber media) were identified as potential candidate technologies to be used for the advanced filtration system. Sample electret and nanofiber media were obtained from manufacturers and tested to explore the feasibility of developing the advanced filtration system.

To evaluate the candidate technologies, performance goals were established for the advanced filtration system based on the following criteria: (a) the technology has better performance than the high-efficiency filters (MERV 14, 15, and 16) available in the market and (b) the technology does not exceed the pressure drop limit that common HVAC systems can accommodate. The performance goals were thus established as follows: 99.9% efficiency for 1-μm particle and a pressure drop of less than 0.5 in. H_2O.

Three candidate nanofiber media with different levels of target efficiencies were tested, and the results showed their performance to be significantly lower than the performance goals. Therefore, the nanofiber media were excluded from further consideration for use in an advanced filtration system.

From the tests conducted on the eight candidate electret media (from seven manufacturers), only one (Sample G) demonstrated both collection efficiency and airflow resistance close to the performance goals. Both the initial and the minimum collection efficiencies of Sample G (the latter was determined after laboratory conditioning) can meet the efficiency goal of 99.9% for 1-μm diameter particles. The initial airflow resistance, however, was approximately 6% higher than the performance goal. The slightly higher airflow resistance can most likely be reduced by enhancing the filter media design area to over 100 ft^2, which is attainable since a typical high-efficiency HVAC filter (pleat) usually has media areas ranging from 100 to 180 ft^2.

In conclusion, the test results with Sample G media showed the potential to develop an advanced electret filter that can meet the performance goals. However, improved electret media, with more stable collection efficiency (over time) than that of the Sample G media are already being developed by the manufacturer. These new media are expected to be commercially available soon. For these reasons, no further development of an advanced filtration system was performed in this project.

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Appendix A
Descriptions of the Databases Searched

Table A-1. Descriptions of the Databases Searched

Database	Producer	File Size	Content/Description
CBIAC	Chemical Warfare/ Chemical and Biological Defense Information Analysis Center (CBIAC)	More than 1.4 million records	The **CBIAC**, operated by Battelle, is a full-service Department of Defense (DoD) Information Analysis Center (IAC). The CBIAC maintains a database containing more than 103,000 document citations, as well as an on-site collection of more than 38,000 books, technical reports, videotapes, and magnetic diskettes from domestic and foreign sources.
DTIC	The Defense Technical Information Center	More than 2 million records	The **DTIC** databases contain technical reports, patents, journal articles, conference proceedings, thesis related to defense-sponsored research, development, test, and evaluation efforts.
CA Search	Chemical Abstracts Service (CAS)	More than 22.2 million records	The **CA Search** database covers all areas of biochemistry, chemistry, and chemical engineering. It contains records for documents reported in printed Chemical Abstracts (CA). The records come from the 1,300 core journals and patents from 26 countries and 2 international patent organizations. Technical reports, books, conference proceedings, and dissertations are also included.
NTIS	National Technical Information Service	More than 2.2 million records	The **National Technical Information Service** database contains abstracts on government-sponsored research, which corresponds to Government Reports Announcement & Index. The file contains records for all areas of science, engineering, and technology. The sources are publications on research, development, and engineering projects sponsored by U.S. and other governments.
Energy SciTec	Office of Scientific and Technical Information, U.S. Department of Energy	More than 4.4 million records	The **Energy Science & Technology** database covers worldwide literature on energy research and technology for all kinds of energy sources, including environmental and other related aspects. Citations in the database are from journals, series, reports, conference papers, books, and patents.
Ei Compendex	Elsevier Engineering Information, Inc.	More than 4.6 million records	The **Ei Compendex**® database is the machine-readable version of the Engineering Index, which provides abstracted information from the world's significant engineering and technological literature. The Compendex database provides worldwide coverage of approximately 4,500 journals and selected government reports and books. The database covers all engineering disciplines, including chemical, energy, environmental, biological engineering, etc.

Table A-1. Descriptions of the Databases Searched (Continued)

Database	Producer	File Size	Content/Description
SciSearch	Institute for Scientific Information (ISI)	More than 12.1 million records	The **SciSearch**®, a cited reference science database, is an international, multidisciplinary index to the literature of science, technology, biomedicine, and related disciplines. SciSearch contains all of the records published in the Science Citation Index® (SCI®), plus additional records in engineering technology, physical sciences, agriculture, biology, environmental sciences, clinical medicine, and the life sciences. SciSearch indexes all significant items (articles, review papers, meeting abstracts, letters, editorials, book reviews, correction notices, etc.) from more than 6,100 international scientific and technical journals.
Biosis Previews	BIOSIS	More than 20 million records	The **BIOSIS Previews**® database contains citations from Biological Abstracts® (BA), and Biological Abstracts/Reports, Reviews, and Meetings® (BA/RRM). The database provides comprehensive worldwide coverage of research in the biological and biomedical sciences.
Enviroline	Congressional Information Service, Inc.	More than 0.3 million records	The **Enviroline**® database covers the world's environmental related information. It provides indexing and abstracting coverage of more than 1,000 international primary and secondary publications reporting on all aspects of the environment. Enviroline corresponds to the print Environment Abstracts.
World Textiles	Elsevier	More than 0.3 million records	The **World Textiles**™ database covers the worldwide literature on the science and technology of textiles and related materials. The database, which includes the coverage of World Textile Abstracts, offers comprehensive coverage of the world's textile-related literature from technical, scientific, economic, and commercial journals, and statistical publications. In addition, World Textiles™ includes unique coverage of the related patents and patent applications from the US, European, and British patent offices.
Textile Technology Digest	Institute of Textile Technology	More than 0.3 million records	The **Textile Technology Digest** database provides international coverage of the literature of textiles and related subjects. Coverage includes the various aspects of textile production and processing. Textile Technology Digest corresponds to the print publication of the same name.

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